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# Thermal and Mechanical Property Characterization of the Advanced Disk Alloy LSHR

Timothy P. Gabb, John Gayda, and Jack Telesman  
Glenn Research Center, Cleveland, Ohio

Peter T. Kantzos  
Ohio Aerospace Institute, Brook Park, Ohio

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Space Administration

Glenn Research Center

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# **Thermal and Mechanical Property Characterization of the Advanced Disk Alloy LSHR**

Timothy P. Gabb, John Gayda, and Jack Telesman  
National Aeronautics and Space Administration  
Glenn Research Center  
Cleveland, Ohio 44135

Peter T. Kantzos  
Ohio Aerospace Institute  
Brook Park, Ohio 44142

## **Abstract**

A low solvus, high refractory (LSHR) powder metallurgy disk alloy was recently designed using experimental screening and statistical modeling of composition and processing variables on sub-scale disks to have versatile processing-property capabilities for advanced disk applications. The objective of the present study was to produce a scaled-up disk and apply varied heat treat processes to enable full-scale demonstration of LSHR properties. Scaled-up disks were produced, heat treated, sectioned, and then machined into specimens for mechanical testing. Results indicate the LSHR alloy can be processed to produce fine and coarse grain microstructures with differing combinations of strength and time-dependent mechanical properties, for application at temperatures exceeding 1300 °F.

## **Introduction**

A series of experimental powder metallurgy disk alloys were recently evaluated for their processing characteristics and high temperature mechanical properties (ref. 1). Disks were subsolvus and supersolvus heat treated, then quenched using procedures designed to reproduce the cooling paths expected in large-scale disks. Mechanical tests were then performed at 1000, 1300, and 1500 °F. Several alloys had superior tensile and creep properties at 1300 °F and higher temperatures, but were difficult to process and prone to quench cracking, chiefly due to their high gamma prime solvus temperature. Several other alloys had more favorable processing characteristics due to their lower gamma prime solvus temperature and balanced time-dependent properties at 1300 °F. Results indicated an experimental low solvus, high refractory (LSHR) alloy could build upon the best attributes of all these alloys, giving exceptional tensile and creep properties at high temperatures with versatile processing characteristics due to a low gamma prime solvus.

The objective of this study was to verify the mechanical properties of this LSHR alloy using scaled-up material processing and disks. This would enable assessments of the processing-property and maximum temperature capabilities of this disk alloy for different potential applications in the engine community. Scaled-up disks were processed, machined into specimens, and tested in tensile, creep, fatigue, and fatigue crack growth tests by NASA Glenn Research Center (GRC) and test vendors. Results were compared to data previously generated on specimens from subscale disks.

## Materials and Procedure

Powder of LSHR superalloy having the composition in weight percent listed in table 1 was atomized by Special Metals Corp. in argon and passed through screens of -270 mesh to give powder particle diameters of no more than about 55  $\mu\text{m}$ . The powder was then sealed in a stainless steel container, hot compacted, and extruded at a reduction ratio of 6:1. Segments of the extrusion billet were machined to mults 6 in. diameter and 8 in. long, then isothermally forged into flat disks about 12 in. diameter and 2 in. thick by Wyman-Gordon Forgings. Two contoured disks were then prepared with an outer diameter of near 12 in., maximum bore thickness of near 2 in., and rim thickness of near 1.5 in. (ref. 18). These disks were then solution heat treated at Ladish, Co. either above or below the gamma prime solvus temperature, estimated at about 2120 °F. A “supersolvus” disk was solution heat treated at about 2140 °F for 2.5 h, then rapidly transferred, in under 30 seconds, to a station for fan cooling. The “subsolvus” disk was solution heat treated at about 2070 °F for 2.5 h, then rapidly transferred, in under 30 seconds, for a quench immersion in agitated oil. These quenching procedures were selected to typify those employed in quenching supersolvus and subsolvus disks of current alloys. The disks were then given a simple aging heat treatment of about 1500 °F for 8 h.

A spare disk of the same dimensions was prepared with numerous thermocouples embedded at different depths in the bore, web, and rim, then given the same supersolvus and subsolvus solution heat treatments. As expected, the oil-quenched subsolvus heat treatment produced much faster average cooling rates of 275 to 730 °F/min. than the fan air quenched supersolvus heat treatment of 65 to 165 °F/min. The temperature-time data recorded from the thermocouples during fan air and oil quenching cycles were analyzed using a commercial heat transfer computer code in order to assign approximate cooling rates, averaged over the temperature range of solution temperature to 1600 °F, for each specimen.

Thermophysical properties were measured on duplicate samples from supersolvus and subsolvus disks by Thermophysical Properties Research Laboratory, Inc. (TPRL) and GRC. Thermal diffusivity ( $\alpha$ ) was measured at TPRL using the laser flash technique according to ASTM E1461. Specific heat ( $C_p$ ) was measured at TPRL using a differential scanning calorimeter according to ASTM E1269. Density ( $d$ ) was measured at GRC using the immersion technique with a methyl ethyl ketone solution, in general accordance with ASTM B311. Thermal conductivity ( $\lambda$ ) values were calculated using the equation:

$$\lambda = \alpha C_p d.$$

Thermal expansion was measured at TPRL using a push-rod dilatometer according to ASTM E228. The mean coefficient of thermal expansion was calculated using the change in length from that at a reference temperature ( $T_0$ ) of 70 °F using the equation:

$$\text{Mean CTE} = ((L_T - L_0)/L_0)/(T - T_0).$$

Elastic modulus was measured at GRC using the impulse excitation technique according to ASTM E1875. Young's modulus was measured from 70 to 2000 °F. Shear modulus was measured at 70 °F. Poisson's ratio ( $\mu$ ) was then calculated for 70 °F using the equation:

$$\mu = (E/2G) - 1 .$$

An extensive mechanical testing matrix was employed for the scaled-up disks included tensile, notched tensile, creep, low cycle fatigue, and fatigue crack growth tests. Tests were performed on specimens from both supersolvus and subsolvus heat treated disks. Tensile tests were performed at temperatures of 75 to 1500 °F. Creep tests were performed from 1200 to 1500 °F. Low cycle fatigue tests were performed at 800 and 1300 °F. Cyclic crack growth tests were performed from 75 to 1300 °F, while dwell crack growth tests were performed at 1200 and 1300 °F.

## Tensile Tests

Tensile tests were performed at Westmoreland Mechanical Testing & Research, Inc. (WMTR) and GRC on specimens machined by WMTR having a gage diameter of 0.16 in. and gage length of 1 in. in uniaxial test machines employing a resistance heating furnace and axial extensometer. The tests were performed according to ASTM E21, using an initial test segment with strain increased at a uniform rate of 0.2 percent/min., followed by a segment with displacement increased at a uniform rate of 0.2 in./min. Notched tensile specimen machining and testing were performed using specimens having a minimum gage diameter of 0.16 in. and stress concentration factor  $K_t = 3.5$  in a uniaxial test machine. Notch tensile tests were performed according to ASTM E602.

## Creep Tests

Machining and testing of scaled-up disk creep specimens were performed by WMTR. Specimens having a gage diameter of 0.25 in. and gage length of 1.5 in. were machined and tested in uniaxial lever arm constant load creep frames using resistance heating furnaces and shoulder-mounted extensometers. The creep tests were performed according to ASTM E139.

## Fatigue Tests

Machining and testing of low cycle fatigue specimens having a uniform gage diameter of 0.25 in. across a gage length of 0.75 in. were performed by WMTR. The low cycle fatigue (LCF) specimens were tested using uniaxial closed-loop servo-hydraulic testing machines with resistance heating furnaces and axial extensometers. Tests were performed according to ASTM E606. A frequency of 0.33 hertz was employed in strain-controlled fatigue testing for the first 6 hours of cycling. A strain ratio ( $R_\epsilon = \epsilon_{\min}/\epsilon_{\max}$ ) of 0 was used. After 6 hours of testing in this manner, surviving specimens were then cycled to the same stabilized stresses using a load-controlled cycle at a faster frequency of 10 hertz until failure.

Machining of a smaller number of cylindrical notched fatigue specimens having a notch diameter of 0.188 in. and geometric stress concentration factor  $K_t$  of 2.0 was performed by WMTR. These specimens were tested using a uniaxial closed-loop servo-hydraulic testing machine with a resistance heating furnace at NASA GRC, to screen notch effects on fatigue life. Tests were performed according to ASTM E466. A frequency of 10 hertz was employed in load-controlled cycles with a stress ratio ( $R_\sigma = \sigma_{\min}/\sigma_{\max}$ ) of 0.05 in most tests. Several additional tests were performed at GRC with a superimposed dwell of 90 s at maximum stress in each cycle.

## Fatigue Crack Growth Tests

Machining of fatigue crack growth specimens from scaled-up disks was performed by WMTR. All specimens had a rectangular gage section 0.4 in. wide and 0.18 in. thick, with a surface flaw (ref. 2) on one side of the gage section about 0.014 in. wide and 0.007 in. deep, produced by electro-discharge machining. The fatigue crack growth specimens were then tested at GRC in general accordance with ASTM E647. Tests were performed in a closed-loop servohydraulic test machine using resistance heating and potential drop measurement of crack growth. Precracking was performed at room temperature. Tests were then performed at elevated temperatures using a maximum stress of 90 ksi. Cyclic tests were performed at a frequency of 0.33 hertz. Dwell tests were performed with a 90 s dwell at maximum stress in each cycle. A stress ratio ( $R_\sigma = \sigma_{\min}/\sigma_{\max}$ ) of 0.05 was used in all crack growth tests.

Fracture surfaces of selected specimens were evaluated by scanning electron microscopy. Cracking modes and grain sizes were also examined on metallographically prepared sections. Grain sizes were determined from grip sections of tensile specimens according to ASTM E112 linear intercept procedures using circular grid overlays, and As-Large-As (ALA) grain sizes were determined using E930. Precipitate and carbide microstructures and phase chemistries were also inspected from these specimens using field emission scanning electron microscopy (FESEM) with energy dispersive X-ray spectroscopy (EDS). Phase extractions were employed on tensile specimen grip sections to enable determination of  $\gamma'$  and  $\gamma$  phase chemistries using inductively coupled plasma mass spectrometry. X-ray diffraction was used on filtered extraction residues to verify  $\gamma'$  and carbide phase identities and lattice parameters. The electrolyte for  $\gamma/\gamma'$  phase extraction was 10 g per liter of citric acid and 10 g per liter of ammonium sulfate in deionized water. The electrolyte for carbide phase extraction was 90 percent methanol and 10 percent HCl by volume with 10 grams per liter of tartaric acid. Transmission electron microscopy on thinned foils was employed where necessary to confirm minor phase chemistry and crystal structure, using EDS and selected area diffraction patterns.

## Results and Discussion

### Material and Microstructures

The actual chemistry in weight percent of the LSHR alloy is listed in table 1. Typical grain microstructures in optical images of etched metallographic sections of tensile specimen grip sections are shown in figure 1. These tensile specimens were from the disks' bore regions cooled more slowly during quenching, and rim regions cooled more quickly. Supersolvus specimens had ASTM mean grain sizes (G) of 7.1 (31  $\mu\text{m}$ ) for the bore and 6.8 (34  $\mu\text{m}$ ) for the rim. The bore and rim specimens had ALA grain sizes of 3.5 (105  $\mu\text{m}$ ) and 2.5 (150  $\mu\text{m}$ ), respectively. Subsolvus specimens had a mean grain size of 11.3 (7.3  $\mu\text{m}$ ) for the bore and 11.0 (8  $\mu\text{m}$ ) for the rim, with ALA grain sizes of 7.5 (27  $\mu\text{m}$ ) and 8.5 (19  $\mu\text{m}$ ). Subsolvus specimens had coarse, undissolved "primary"  $\gamma'$  particles spaced along grain boundaries and sometimes widely scattered within grains.

The typical minor phases observed are shown in the FESEM images of figure 2. Relatively large, angular precipitates between 0.3 and 1.5  $\mu\text{m}$  in diameter were observed within grains and sometimes at grain boundaries. They were determined by energy dispersive x-ray spectroscopy (EDS) analyses to contain tungsten, molybdenum, chromium, and boron. FESEM EDS and TEM selected area diffraction patterns indicated they were  $(\text{W},\text{Mo},\text{Cr})_3\text{B}_2$  particles, as shown in figure 3. Smaller MC carbides between 0.2 and 0.5  $\mu\text{m}$  in diameter were also scattered within the grains. They were determined by EDS analyses to also contain tantalum, niobium, and titanium. FESEM EDS and TEM microdiffraction patterns indicated they were  $(\text{Ta},\text{Nb},\text{Ti})\text{C}$  particles, as shown in figure 3. Very fine  $\text{M}_{23}\text{C}_6$  carbides between 0.05 and 0.2  $\mu\text{m}$  in thickness were observed along many grain boundaries. EDS was more difficult for these very fine carbides due to background  $\gamma-\gamma'$  peak interferences, but these carbides appeared to contain Cr, W, and Mo.

Typical  $\gamma'$  precipitate microstructures from tensile specimen grip sections are also shown in field emission microscopy images of figure 4. Within the grains of the supersolvus specimen from the disk bore, three populations of  $\gamma'$  precipitates were evident. Scattered large precipitates (0.3 to 0.5  $\mu\text{m}$  wide) appeared to have preferentially grown at the cube corners, giving consistently oriented star shapes. Such large precipitates have been observed in previous work (ref. 3), including for bore sections of disk superalloys (ref. 4). Intermediate size precipitates (0.15 to 0.3  $\mu\text{m}$  wide) had a rounded cube shape. They sometimes appeared to be sectioned lobes of the large precipitates, but in other instances appeared to be isolated precipitates. Small quantities of fine, spherical precipitates (0.02 to 0.05  $\mu\text{m}$  wide) were also

observed scattered throughout the microstructure. The supersolvus rim specimen only had simpler, rounded cuboid precipitates 0.1 to 0.25  $\mu\text{m}$  wide, and fine spherical precipitates 0.02 to 0.05  $\mu\text{m}$  wide.

Subsolvus specimens had less distinct differences in  $\gamma'$  precipitates between the bore and rim locations. Bore specimens had rounded cuboid precipitates 0.1 to 0.25  $\mu\text{m}$  wide, with minor preferential growth of some corners for scattered large particles. Rim specimens had round cuboid precipitates 0.08 to 0.15  $\mu\text{m}$  wide. Both bore and rim specimens had fine spherical precipitates 0.01 to 0.03  $\mu\text{m}$  wide scattered between larger precipitates, and surrounding primary  $\gamma'$  particles. Coarse, undissolved “primary”  $\gamma'$  particles (0.6 to 3  $\mu\text{m}$  wide) were spaced along grain boundaries and sometimes widely scattered within grains.

Both  $\gamma'$  and carbide phase extractions were performed. Averaging over four  $\gamma'$  extractions,  $50.8 \pm 0.4$  weight percent of  $\gamma'$  phase was extracted. However, the 0.1  $\mu\text{m}$  filter employed would be expected to allow the fine precipitates at smaller diameter to pass through. Therefore, the total weight percent of  $\gamma'$  phase was estimated to be between 52 and 54 percent. Chemistries of the extracted  $\gamma$  and  $\gamma'$  phases are listed in table 1, along with the associated  $\gamma$  partitioning ratios defined as:

$$\gamma \text{ partitioning ratio of element E} = (\text{at. \% E in } \gamma) / (\text{at. \% E in } \gamma').$$

Cr, Fe, Mo, and Co strongly partitioned to  $\gamma$ , while Ta, Ti, Nb, and Al strongly partitioned to  $\gamma'$ , as observed in previous studies of superalloys (ref. 5, 6). W partitioned somewhat more to  $\gamma$  than  $\gamma'$ , but was present in both phases.

The unconstrained  $\gamma'$  lattice parameter was measured by X-ray diffraction to be  $3.596 \pm 0.001$  Angstroms. X-ray diffraction of carbide extractions indicated the presence of MC carbides and  $\text{M}_3\text{B}_2$  borides, along with residual  $\gamma'$ . However,  $\text{M}_{23}\text{C}_6$  carbides were not detected in the carbide extractions. It was again expected that these very fine  $\text{M}_{23}\text{C}_6$  carbides passed through the 0.1  $\mu\text{m}$  filter, and were therefore not successfully isolated. These results were typical of other disk superalloys (ref. 6).

### Physical and Thermal Properties

Thermal diffusivity is shown as a function of temperature in figure 5. Thermal diffusivity increased linearly from 0.102  $\text{ft}^2/\text{h}$  at 70  $^\circ\text{F}$  to 0.18  $\text{ft}^2/\text{h}$  at 1500  $^\circ\text{F}$ , then was relatively stable to 2100  $^\circ\text{F}$ . Specific heat results are shown as a function of temperature in figure 6. Specific heat increased from about 0.10 BTU/(lb-F) at 70  $^\circ\text{F}$  to 0.28 BTU/(lb-F) at 2030  $^\circ\text{F}$  for subsolvus specimens, then dropped off. Specific heat increased to about 0.30 BTU/(lb-F) at 2080  $^\circ\text{F}$  for supersolvus specimens, then dropped off. The density of subsolvus and supersolvus disk specimens was measured to be  $0.302 \pm 0.0005 \text{ lb/in}^3$ , as given in table 2. Calculated thermal conductivity values are shown as a function of temperature in figure 7. Thermal conductivity increased approximately linearly from 5.4 BTU/(h-ft-F) at 70  $^\circ\text{F}$  to 16.3 BTU/(h-ft-F) at 2200  $^\circ\text{F}$ , with slight positive divergence near 1500  $^\circ\text{F}$ . Thermal expansion, instantaneous CTE, and mean CTE are shown as functions of temperature in figure 8. Mean CTE increased from 6.8  $\mu\text{in}/(\text{in.-F})$  at 70  $^\circ\text{F}$  to a plateau at 10.6  $\mu\text{in}/(\text{in.-F})$  near 2100  $^\circ\text{F}$ . Young's modulus is shown as a function of temperature in figure 9. Young's modulus (E) decreased from about 32.8 Msi at 70  $^\circ\text{F}$  to about 17.5 Msi at 2000  $^\circ\text{F}$ . Shear modulus (G) and Young's modulus at 70  $^\circ\text{F}$  were measured to be 12.73 and 32.74 Msi, and Poisson's ratio ( $\mu$ ) was then calculated to be 0.286 at this temperature, table 3. These results were in general agreement with those obtained from other similar nickel-base superalloys (ref. 7). The test results are tabulated in appendixes 1 through 8.

## Tensile Stress-Strain Response

Yield strengths at 0.2 percent offset, ultimate strengths, notched strength, percent elongation after failure, and percent reduction in area after failure are compared as functions of temperature in figures 10 and 11. Polynomial regression was performed on these responses using temperature ( $T$ ),  $T^2$ , and  $T^3$  as the independent variables. The resulting equations and correlation coefficients are listed in the figures, for use in estimating mean strengths and ductilities. Supersolvus yield strength was sustained up to a temperature of 1400 °F, then dropped off with increasing temperature. Subsolvus yield strength was 20 to 30 ksi higher than supersolvus levels, but began dropping at 1300 °F. A similar strength differential between supersolvus and subsolvus specimens applied to ultimate strength. Ultimate strength began dropping off above 1200 °F for supersolvus material, and above 1100 °F for subsolvus material. Notched tensile strengths ran 30 to 50 ksi higher than ultimate strength, with ratios of notched over ultimate strength always exceeding 1.1. Elongation and reduction in area had more variability than strengths, but averaged relatively constant as functions of temperature up to 1300 °F for supersolvus specimens, and up to near 1100 °F for subsolvus specimens. Both then decreased with increasing temperature. Test results of specimens from scaled-up disks are also compared to previously published (ref. 1) subscale LSHR disk results in figures 10 and 11. The scaled-up disks had comparable tensile strength and ductility compared to the subscale disks. These results were also typical of similar disk alloys tested in that study. Tensile strengths often exceeded those reported from powder metallurgy disks of Udimet 720 (refs. 8 to 10) and ME3 (ref. 11). The test results are tabulated in appendixes 8 and 9.

The variabilities of elongation and reduction in area observed in the tensile tests were largely due to cooling rate variations among the test specimens. Strengths and ductilities of full-scale disk specimens are shown versus approximate cooling rate in figures 12 and 13. For the cooling rates encompassed by the disks and associated test specimens, increasing cooling rate sometimes slightly increased yield strength, while ultimate strength was not consistently affected. However, increasing cooling rate significantly decreased elongation and reduction in area at test temperatures of 1300 °F and higher. This was more consistently observed in the elongation measurements, where regression lines are included in the figure. It should be noted that elongation measurements on failed specimens were inherently less difficult to perform and more reproducible than reduction in area measurements, which required final diameter measurements across fracture surfaces of varying irregularity.

Typical tensile fracture surfaces at various temperatures are compared for supersolvus specimens in figure 14 and for subsolvus specimens in figure 15. Supersolvus and subsolvus tensile specimens had predominantly transgranular failure modes by microvoid coalescence in tests from room temperature to 1200 °F. At these temperatures, scattered slip “facet” grain failures were also observed. At higher temperatures of 1300 to 1500 °F, oxidized intergranular surface cracks appeared to first occur, followed by transgranular microvoid coalescence failure in the center of the specimens. Evidently, environmental attack weakened grain boundaries in comparison to grain interiors with increasing temperature. No large differences were observed in general failure modes between low cooling rate specimens exhibiting high ductility and high cooling rate specimens exhibiting low ductility in tests at 1300 to 1500 °F. However, the supersolvus grain surfaces exposed in intergranular surface cracks for low cooling rate specimens did show larger perturbations than for high cooling rate specimens. These perturbations are attributable to the selectively coarsened large  $\gamma'$  precipitates spaced along many grain boundaries in slow cooling rate specimens, producing serrated grain boundaries for the bore specimen as shown in figure 1.

## Creep Properties

Time to 0.2 percent creep ( $t$ ) and rupture of creep tests at temperatures ( $T$ ) of 1200, 1300, 1400, and 1500 °F were analyzed using the Larson-Miller approach commonly employed for disk alloys. Creep

results were used to generate conventional Larson-Miller curves of stress versus Larson-Miller parameter (LMP) using the equation:

$$\text{LMP} = (T + 460 \text{ }^\circ\text{R})(\log t + C)/1000$$

The resulting plots are shown in figures 16 and 17. It can be seen that the LMP constant  $C = 20$  did not fully account for test temperature in modeling the time to produce low creep strains of 0.2 percent, but worked reasonably well for rupture life. Regressions indicated a constant of 28 gave the highest correlations for 0.2 percent creep lives in both supersolvus and subsolvus material. Polynomial regression equations using the variables LMP and  $\text{LMP}^2$  are included with correlation coefficients in the figures, for use in estimating mean life responses as functions of temperature and stress using this Larson-Miller approach. Test results previously generated from specimens of subscale LSHR disks are also compared to the scaled-up results in figures 16 and 17. The scaled-up material had equal or higher creep lives compared to the sub-scale disks. Supersolvus creep results slightly exceeded that observed for ME3 (ref. 11), while subsolvus creep results significantly exceeded that reported for Udimet 720 (ref. 9).

Times to 0.2 percent creep of the scaled-up disk specimens are shown versus approximate cooling rate in figure 18. Increased cooling rate improved creep life at low temperatures of 1200 to 1300 °F, but reduced creep life at higher temperatures of 1500 °F for supersolvus material and 1400 °F for subsolvus material. The cooling rate effects on creep life were less than 2X for supersolvus material, but could exceed 3X for subsolvus material over the range of cooling rates evaluated. The test results are tabulated in appendix 10.

Supersolvus and subsolvus creep specimens tended to fail from intergranular, surface-initiated cracks at the creep test temperatures of 1200 to 1500 °F, as shown in figures 19 and 20. This was apparently due to environmental attack at grain boundaries. At higher temperatures of 1400 to 1500 °F, exposed grain surfaces on the surface cracks had a more rough, dimpled morphology and more secondary cracking, with evident grain boundary cavitation. The final overload failure occurred by transgranular microvoid coalescence with scattered “facet” crystallographic grain failures at 1200 °F. At increasing temperatures of 1300 to 1500 °F, the final overload regions had increasing area fractions of intergranular failure by cavitation at grain boundaries, increasing from 25 percent at 1300 °F to 80 percent at 1500 °F.

Several failed creep specimens with rupture lives of over 3000 hours at 1300 °F were sectioned and metallographically prepared. FESEM evaluations could find no deleterious topologically close packed phases had yet formed. Additional creep tests with test conditions designed for longer rupture lives are currently in test and will be evaluated in a like manner after failure.

## Fatigue Properties

**Uniform gage tests.**—Total strain range versus fatigue life is compared at the test temperatures of 800 and 1300 °F for supersolvus and subsolvus materials with uniform gage specimens in figure 21. Sub-solvus material had 2 to 5x higher lives than supersolvus material at 800 °F, with larger differences apparent at low strain ranges. At 1300 °F, subsolvus and supersolvus lives were nearly comparable at high strain ranges, but subsolvus exceeded supersolvus lives by nearly 3x at low strains. This could be due to the higher yield strength of subsolvus over supersolvus materials, allowing less plastic strain and associated damage in each fatigue cycle of a given strain range.

At high strain ranges, fatigue life was higher in tests at 800 °F than at 1300 °F, for both subsolvus and supersolvus materials. This could be due to the higher yield strengths of both materials at 800 °F than 1300 °F, which allowed less plastic strain and associated damage in each fatigue cycle of a given strain range than at 1300 °F. The higher ductilities observed at 800 °F than 1300 °F could also allow more accumulated strain damage before failure initiation. However, at low strain ranges near 0.6 percent, fatigue life was higher in tests at 1300 °F than at 800 °F, for both subsolvus and supersolvus material.

This could be mainly due to the lower yield strength at 1300 °F, which can allow more reductions in positive stresses by way of yielding in tension, both for initial stresses and after repeated cycling or “cyclic shakedown.” This could also be related to a higher tolerance of fatigue defects such as large grains and inclusions at the higher temperature, where plastic deformation within grains appeared to be more uniform with no observable slip offsets. The supersolvus material fatigue results were generally comparable to those obtained for ME3 (ref. 11), while the subsolvus fatigue results were generally comparable to that obtained for Udimet 720 (refs. 8 to 10).

A substantial variation in lives is sometimes evident for multiple tests performed at the same strain range. While some scatter is to be expected in fatigue lives, this scatter was also often found to be related to the effects of increasing yield strength with increasing cooling rate, and resulting differences in maximum and minimum stresses generated in strain-controlled tests at the same strain and stress range of different specimens. Maximum stress and stress range as functions of cycles are compared for subsolvus rim and bore specimens both tested at a total strain range of 0.8 percent and 1300 °F in figure 22. These comparative specimens run at the same conditions were purposefully chosen from different locations in the disks, to encompass a wide range of cooling rates. The specimen from the faster cooling rim had more positive maximum stresses than the specimen from the slower cooling bore in tests producing comparable stress ranges, and lower fatigue life. This was the case both for initial stresses generated as the strain range was gradually increased to 0.8 percent, and after cyclic shakedown. Such differences in maximum stresses ( $\sigma_{\max}$ ) and minimum stresses ( $\sigma_{\min}$ ), in tests at about the same stress range ( $\Delta\sigma$ ) and strain range ( $\Delta\varepsilon$ ) could be accounted for using an approach of Smith-Watson-Topper (ref. 12):

$$\sigma_{\text{swt}} = (\sigma_{\max}\Delta\sigma/2)^{0.5}$$

This relationship accounts for differences in maximum stress as well as stress range. Resulting plots of  $\sigma_{\text{swt}}$  versus fatigue life are compared at the test temperatures of 800 and 1300 °F for supersolvus and subsolvus materials with uniform gage specimens in figure 23. Usage of this  $\sigma_{\text{swt}}$  parameter or similar approaches to account for differences in maximum and minimum stresses is seen to reduce scatter, and allowed improved correlations in polynomial regressions. The test results are tabulated in appendix 11.

Supersolvus low cycle fatigue specimens predominantly failed from cracks initiated by planar failure of relatively large grains on the specimen surface at 800 °F, as shown in figure 24. These “faceted” grain failures (refs. 11 and 13) appeared to be due to concentrated slip on crystallographic planes, which sometimes produced noticeable slip offsets on the surfaces of large grains, as shown in figure 25. The grain facets were mostly flat with least texture in tests at 800 °F. At 1300 °F, a majority of specimens tested at low strain ranges of 0.6 to 0.8 percent again failed from grain facets. At the lowest strain range of 0.6 percent, the failure initiation sites shifted to internal grains rather than surface grains. The grain facets had more texture in tests at 1300 °F. At higher strain ranges of 0.8 to 1.2 percent, more specimens failed from oxidized surface cracks. These surface cracks were often, but not always intergranular. At both temperatures, more cracks were initiated in tests at higher strain ranges. A much smaller minority of supersolvus specimens failed at 1300 °F from ceramic inclusions. The inclusions initiating failures were evenly segregated between angular, silicon or calcium-rich oxide inclusions broken up into several pieces, often referred to as Type 1 inclusions, and granulated, reactive aluminum-rich oxide Type 2 inclusions (refs. 14 and 15).

Subsolvus low cycle fatigue specimens failed either from grain facets, pores, or inclusions at 800 °F, as shown in figure 26. The grain facets were much smaller than for supersolvus specimens, due to the finer grain size. At 1300 °F, a majority of specimens tested at all strain ranges again failed from inclusions. Several specimens had grain facet initiated failures. At both temperatures, more cracks were again initiated in tests at higher strain ranges. Failures initiated exclusively at the specimen surfaces for strain ranges of 0.8 to 1.2 percent, but often shifted to internal locations at 0.6 percent.

**Notched fatigue tests.**—Maximum stress across the notched diameter is compared versus fatigue life at the test temperatures of 800 and 1300 °F for supersolvus and subsolvus notched fatigue specimens in

figure 27. Subsolvus material had longer cyclic lives than supersolvus material at low applied stresses at 800 °F, and for all applied stresses at 1300 °F.

At highest stresses, cyclic fatigue life was again higher in tests at 800 °F than at 1300 °F, for both subsolvus and supersolvus material. Here also, this could be due to the higher strengths and ductilities of both materials at 800 °F, which allowed less plastic strain and associated damage in each fatigue cycle at a given stress and more damage accommodation than at 1300 °F. However, at lower stresses, fatigue life was again higher in tests at 1300 °F than at 800 °F, for both subsolvus and supersolvus material. As for unnotched specimens, the lower yield strength at 1300 °F could allow more reductions in positive stresses by way of yielding in tension than at 800 °F, both for initial stresses and after cyclic shakedown. It would be expected that these reductions would be localized near the notch tip where concentrated stresses can exceed the yield strength. This local region of yielding, or plastic zone, near the notch tip would be constrained by surrounding material which is only elastically loaded. Therefore, accounting for these differences in stresses is more difficult than for uniform gage specimens and beyond the scope of this study, requiring elastic-plastic finite element modeling of the notched specimen during fatigue cycling. Yet, it could be possible to employ the stress-strain data generated in the uniform gage tests within such a model, to estimate notched specimen stresses for comparison of the notched and smooth gage fatigue lives.

The results of several additional tests performed at 1300 °F with a superimposed dwell of 90 s at maximum stress in each cycle are also shown in figure 27. Supersolvus life was reduced by about 10X in the two dwell tests performed. Subsolvus life was reduced even more, ranging from 10X to 1000X in the two dwell tests performed on this material. Additional tests are necessary to fully quantify the effects of dwells on notched fatigue life as functions of maximum stress in the two materials, but it is clear that dwells at maximum stress can substantially degrade fatigue life at 1300 °F. Understanding the notch-stress response in these tests would require elastic-viscoplastic finite element modeling of both plastic flow and time-dependent relaxation of stresses near the notch during the dwell fatigue cycling. The test results are tabulated in appendix 12.

Supersolvus and subsolvus notched fatigue specimens invariably had failure initiations at the notch tip. Supersolvus and subsolvus specimens tested in cyclic fatigue at 800 °F had multiple transgranular crack initiations at the notch root, and subsequent transgranular crack growth, as shown in figures 28 and 29. At 1300 °F, supersolvus specimens tested in cyclic fatigue again had multiple transgranular crack initiations at the notch root, and subsequent transgranular crack growth. Subsolvus specimens tested in cyclic fatigue at 1300 °F had transgranular crack initiations at the notch root, then mixed intergranular and transgranular crack growth. Both supersolvus and subsolvus specimens tested at 1300 °F with the superimposed 90 s dwells at maximum stress had intergranular crack initiations along the notch tip and subsequent intergranular crack growth, figures 28 and 29. It appears the intergranular crack initiation mode accounted in part for the lower lives of specimens tested at 1300 °F with the superimposed 90 s dwells.

### **Fatigue Crack Growth Properties**

Cyclic crack growth rate versus stress intensity factor range is compared for all test temperatures in figure 30. Crack growth rates at  $25 \text{ ksi}\cdot\text{in}^{0.5}$  are shown versus temperature in figure 31. Crack growth rates increased with temperature, and were consistently lower for supersolvus specimens than for subsolvus specimens. The increase in crack growth rates with temperature was quite modest, increasing roughly 10X in going from 75 to 1300 °F. Supersolvus crack growth rates were 50 to 70 percent of subsolvus crack growth rates at constant temperature. Linear regression equations modeling cyclic crack growth rates versus temperature are included in these figures, for use in estimating mean crack growth responses as a function of temperature.

Dwell crack growth rate versus stress intensity factor range is compared for test temperatures of 1200 and 1300 °F in figure 32. Crack growth rates at  $25 \text{ ksi}\cdot\text{in}^{0.5}$  are shown versus temperature in figure 33. Supersolvus crack growth rates were more substantially lower than subsolvus rates in the dwell tests compared to 0.33 hertz cyclic tests, with supersolvus rates at about 20 percent of subsolvus rates for a given temperature. Linear regression equations modeling dwell crack growth rates at maximum stress intensities of  $25 \text{ ksi}\cdot\text{in}^{0.5}$  versus temperature are included in these figures, for use in estimating mean crack growth responses as a function of temperature. Dwell crack growth rates increased about 10x when increasing temperature from 1200 to 1300 °F. The test results are tabulated in appendix 13.

The cracking modes observed in cyclic fatigue crack growth tests of supersolvus specimens are compared for various temperatures in figure 34. Supersolvus cyclic crack growth specimens had predominantly transgranular cracking at all test temperatures. While the proportion of transgranular cracking was essentially 100 percent at 75 °F, a small percentage of intergranular cracking became apparent at temperatures of 1200 °F (about 5 percent) and 1300 °F (about 10 percent). Specimens tested from 75 to 1200 °F displayed planar cracking of some individual grains by facet failure, possibly related to concentrated slip on crystallographic planes as for the low cycle fatigue specimens. At higher temperatures a more textured fracture morphology was observed which was more nearly Mode 2.

Supersolvus specimens tested in dwell crack growth had predominantly intergranular cracking at the temperatures tested, figure 35. The intergranular cracking mode was mixed with minor transgranular cracking in tests at 1200 °F. The exposed crack growth surfaces were relatively flat, with little secondary cracking. However, the intergranular failure became highly prevalent in tests at 1300 °F, with considerable secondary grain boundary cracks obvious. A metallographic section of the crack growth region was prepared parallel to the loading axis to determine the extent of secondary cracking. As shown in figure 36, the secondary cracks extended down at least one layer of grains.

The cracking modes observed in cyclic fatigue crack growth tests of subsolvus specimens are compared for various temperatures in figure 37. Subsolvus cyclic crack growth specimens had predominantly transgranular cracking in tests at 75 to 800 °F. A much larger percentage of intergranular cracking became apparent than for supersolvus material at temperatures of 1200 °F (about 25 percent) and 1300 °F (about 60 percent). A significant number of secondary intergranular cracks were also observed at these higher test temperatures.

Subsolvus specimens tested in dwell crack growth had predominantly intergranular cracking at 1200 and 1300 °F, figure 38. The intergranular failure was highly prevalent in tests at both 1200 and 1300 °F, with considerable secondary grain boundary cracks obvious. A metallographic section of the crack growth region was prepared parallel to the loading axis to determine the extent of secondary cracking. As shown in figure 39, the secondary cracks extended down several layers of grains.

The crack growth results are in general agreement with previous findings on powder metallurgy disk superalloys. The effects of dwells in accelerating fatigue crack growth have been observed in Rene 95 (ref. 16), Udimet 720 (refs. 8 and 17), and ME3 (ref. 11). Coarser grain microstructures also have been shown superior for dwell fatigue crack growth (refs. 8, 16, and 17).

### **Additional Evaluations of LSHR**

Several additional investigations of this alloy are currently underway, based on the results of these evaluations of scaled-up disks. The effects of cooling rate and aging heat treatments on tensile, creep, stress relaxation, dwell fatigue crack growth, and dwell notched fatigue properties at 1300 °F are being evaluated. Results have indicated that these properties are strongly influenced by varying solution heat treatment cooling rate as well as aging heat treatments. Different balances among these properties are thereby possible with this alloy, including much higher tensile ductility at high temperatures. Advanced dual microstructure heat treatments (DMHT) have also been applied to LSHR. The low solvus temperature of this alloy combined with its high refractory element levels allow very attractive

combinations of properties to be easily attained, giving high strength and fatigue resistance in the fine grain bore, and high creep and dwell crack growth resistance in the coarse grain rim (ref. 18). This advanced solution heat treatment is now being used with subsequent “supercooling” i.e., computer-controlled air quenching technology which carefully controls cooling rate as a function of location on a disk. This control of grain size and cooling rate can be combined with optimal aging heat treatments to produce highly favorable balances of mechanical properties at key disk locations (ref. 19).

## Summary and Conclusions

Scaled-up LSHR disks were processed, sectioned, machined into specimens, and mechanically tested. The measured mechanical properties closely matched those previously determined from subscale disks. The mechanical properties of LSHR can be summarized as follows:

- 1) Tensile: Scaled-up LSHR had stable tensile strength and ductility to at least 1200 °F with a coarse grain, supersolvus heat treatment, and 1100 °F with fine grain, subsolvus heat treatment. Strength and ductility then gradually decreased with increasing temperature at higher temperatures. Ductility at high temperatures decreased with increasing cooling rate. Strength values usually exceeded those reported for ME3 and Udimet 720. Microvoid coalescence within grains produced failure at 75 to 1300 °F, but surface cracking interceded at 1300 to 1500 °F.
- 2) Creep: Supersolvus and subsolvus LSHR had comparable creep resistances at 1200 to 1300 °F, sustaining stresses of up to 100ksi with 0.2 percent creep lives of at least 100 h. At 1400 °F and 1500 °F, this applied stress dropped drastically to about 75 ksi and 50 ksi, respectively. This creep response exceeded those reported for ME3 and Udimet 720. Creep response could be modeled versus temperature and stress using a Larson-Miller Parameter approach, where a Larson Miller constant of 28 worked reasonably well for 0.2 percent creep and constant of 20 for creep rupture. Surface cracking limited rupture life at all test temperatures.
- 3) Low cycle fatigue: At strain ranges of 0.7 percent or less typically encountered in applications, LSHR had good LCF resistance at both 800 and 1300 °F. However, at higher strain ranges, life decreased at 1300 °F compared to 800 °F due to lower strength. Fatigue life response of LSHR was comparable to that reported for ME3 and Udimet 720 at equivalent grain sizes. Crystallographic slip failures of large grains usually initiated failure in supersolvus material in tests at both 800 and 1300 °F. However, at 1300 °F and high strain ranges failures were often produced by crack initiation modes at surface oxidation. Failures of subsolvus material were often initiated by inclusions at both temperatures, though several failures were also initiated by grain facets or pores at 800 °F. Limited tests of notched specimens indicated dwells at maximum stresses significantly degrade fatigue resistance at 1300 °F.
- 4) Crack growth: Cyclic crack growth rates only increased by 10X between 75 and 1300 °F. However, dwell crack growth rates were significantly higher than cyclic rates and increased much more strongly with temperature from 1200 to 1300 °F, by about 10X. Supersolvus material consistently had lower cyclic and dwell crack growth rates than subsolvus material. Crack growth response of LSHR was typical of that reported for ME3 and Udimet 720 at equivalent grain sizes. Dwells at maximum stress promoted intergranular crack growth for both materials.

It can be concluded from this evaluation that LSHR should have at least 1300 °F general capabilities. Subsolvus, fine grain material could be preferred for superior strength, fatigue, and creep resistance at temperatures up to 1200 °F. Supersolvus, coarse grain material should be selected for superior creep and dwell crack growth resistance at higher temperatures. In both cases, LSHR appears to have improved strength and creep resistance over many existing powder metallurgy disk superalloys. More detailed

assessments of mechanical properties versus component design needs would be necessary to determine specific temperature limits for specific potential applications.

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Table 1.—Measured composition in weight percent of LSHR alloy disks, and measured compositions of extracted  $\gamma'$  and  $\gamma$  phases.

Wt%	Al	B	C	Co	Cr	Fe	Mo	Nb	Ta	Ti	W	Zr	Ni
LSHR Composition	<b>3.46</b>	<b>0.028</b>	<b>0.029</b>	<b>20.7</b>	<b>12.52</b>	<b>0.07</b>	<b>2.73</b>	<b>1.45</b>	<b>1.6</b>	<b>3.5</b>	<b>4.33</b>	<b>0.049</b>	<b>49.534</b>
$\gamma'$ phase	5.48			12.27	1.99	0.02	1.1	2.49	3.02	6.36	3.59	0.094	63.586
$\gamma$ phase	1.16	0.019		30.34	23.34	0.095	4.24	0.38	0.19	0.56	4.99	0.002	34.684
$\gamma$ Partitioning Ratio =(at. % $\gamma$ )/(at. % $\gamma'$ )	0.22			2.55	12.10	4.90	3.98	0.16	0.06	0.09	1.43	0.02	0.56

Table 2. —Measured densities of supersolvus and subsolvus samples.

Sample	Dry weight	Wet weight	Buoyancy	Density	Density
	g	g		g/cc	lb/in <sup>3</sup>
Subsolvus 1	8.2292	7.4363	0.7929	8.3589	0.3020
Subsolvus 2	8.1743	7.3862	0.7881	8.3537	0.3018
Subsolvus 3	8.5936	7.7653	0.8283	8.356	0.3019
Subsolvus 4	8.5236	7.7026	0.821	8.3616	0.3021
Subsolvus 5	7.9164	7.1536	0.7628	8.3585	0.3020
Supersolvus	4.0359	3.6481	0.3878	8.3819	0.3028
Supersolvus	4.0295	3.6399	0.3896	8.3300	0.3009
Supersolvus	4.0459	3.6563	0.3896	8.3639	0.3022
Supersolvus	4.0241	3.6364	0.3877	8.3596	0.3020
			<b>MEAN</b>	<b>8.358</b>	<b>0.3020</b>
			<b>STDEV</b>	<b>0.013</b>	<b>0.0005</b>

Table 3.—Shear and Young's modulus measurements at room temperature, with calculated Poisson's ratio.

Spec.	G-Shear Modulus		Spec.	E-Young's Modulus	
	GPa	Msi		GPa	Msi
A1-BL3	87.97	12.76	T7-2-M1	224.95	32.62
A1-WL1	87.55	12.70	T7-2-M1	228.25	33.10
B1-BL3	88.30	12.81	T7-2-M2	224.85	32.61
B1-RL2	87.21	12.65	T7-2-M2	226.96	32.92
<b>Mean</b>	<b>87.76</b>	<b>12.73</b>	T7-2-M3	222.56	32.28
<b>StDev</b>	<b>0.48</b>	<b>0.07</b>	T7-2-M3	226.22	32.81
			T7-2-M4	224.75	32.60
Poisson's Ratio			T7-2-M4	227.17	32.95
=E/(2G)-1			<b>Mean</b>	<b>225.71</b>	<b>32.74</b>
<b>0.286</b>			<b>StDev</b>	<b>1.80</b>	<b>0.26</b>

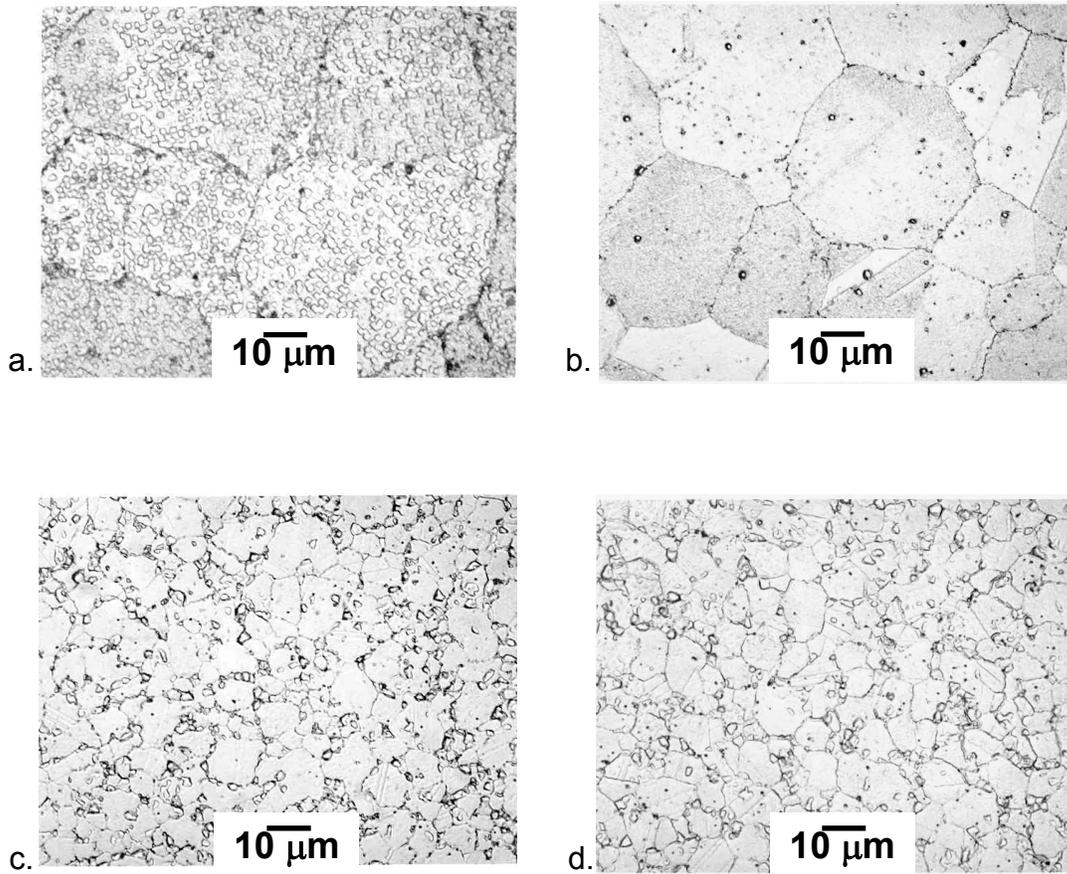


Figure 1.—Optical micrographs of supersolvus and subsolvus disk grain microstructures:  
a. supersolvus bore, b. supersolvus rim, c. subsolvus bore, d. subsolvus rim.

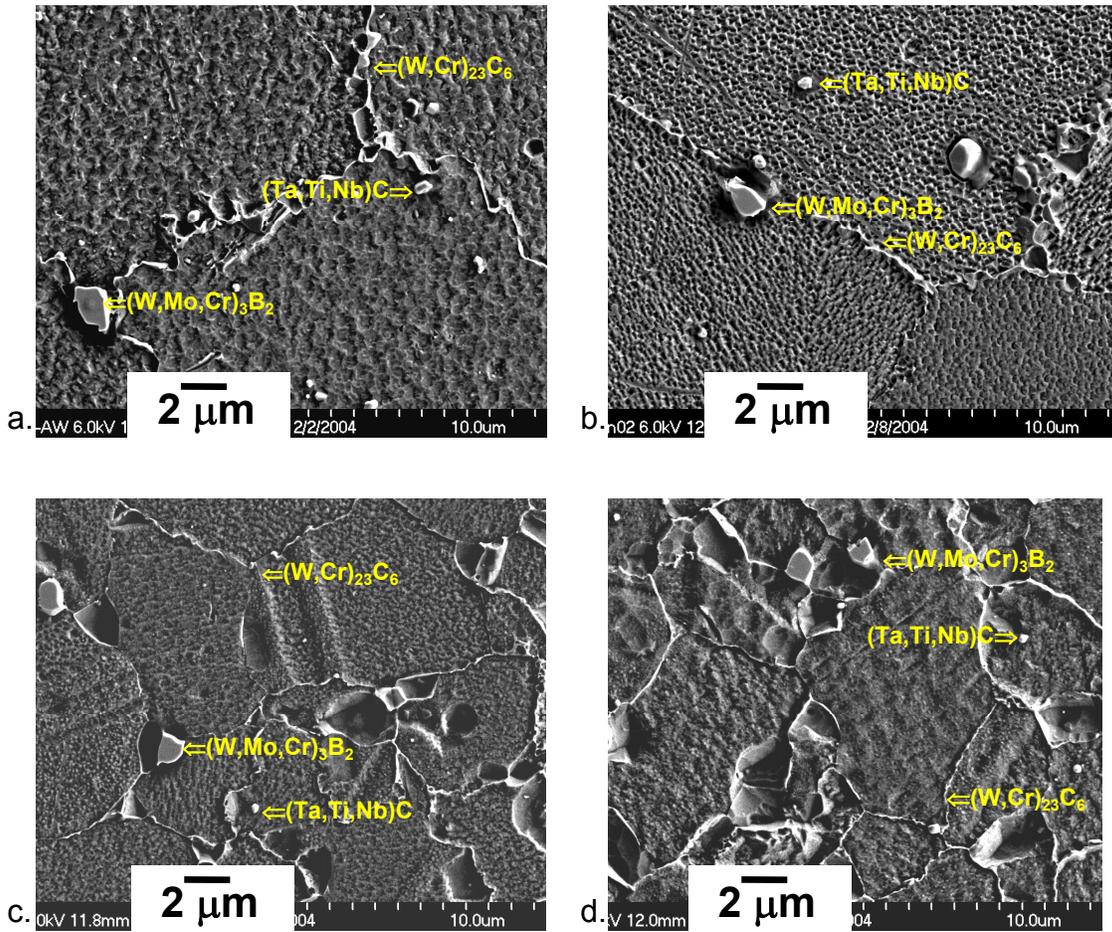


Figure 2.—FESEM micrographs of supersolvus and subsolvus disk microstructures, showing large  $(W, Mo, Cr)_3B_2$ , medium  $(Ta, Ti, Nb)C$ , and fine  $(W, Cr)_{23}C_6$  carbides: a. supersolvus bore, b. supersolvus rim, c. subsolvus bore, d. subsolvus rim.

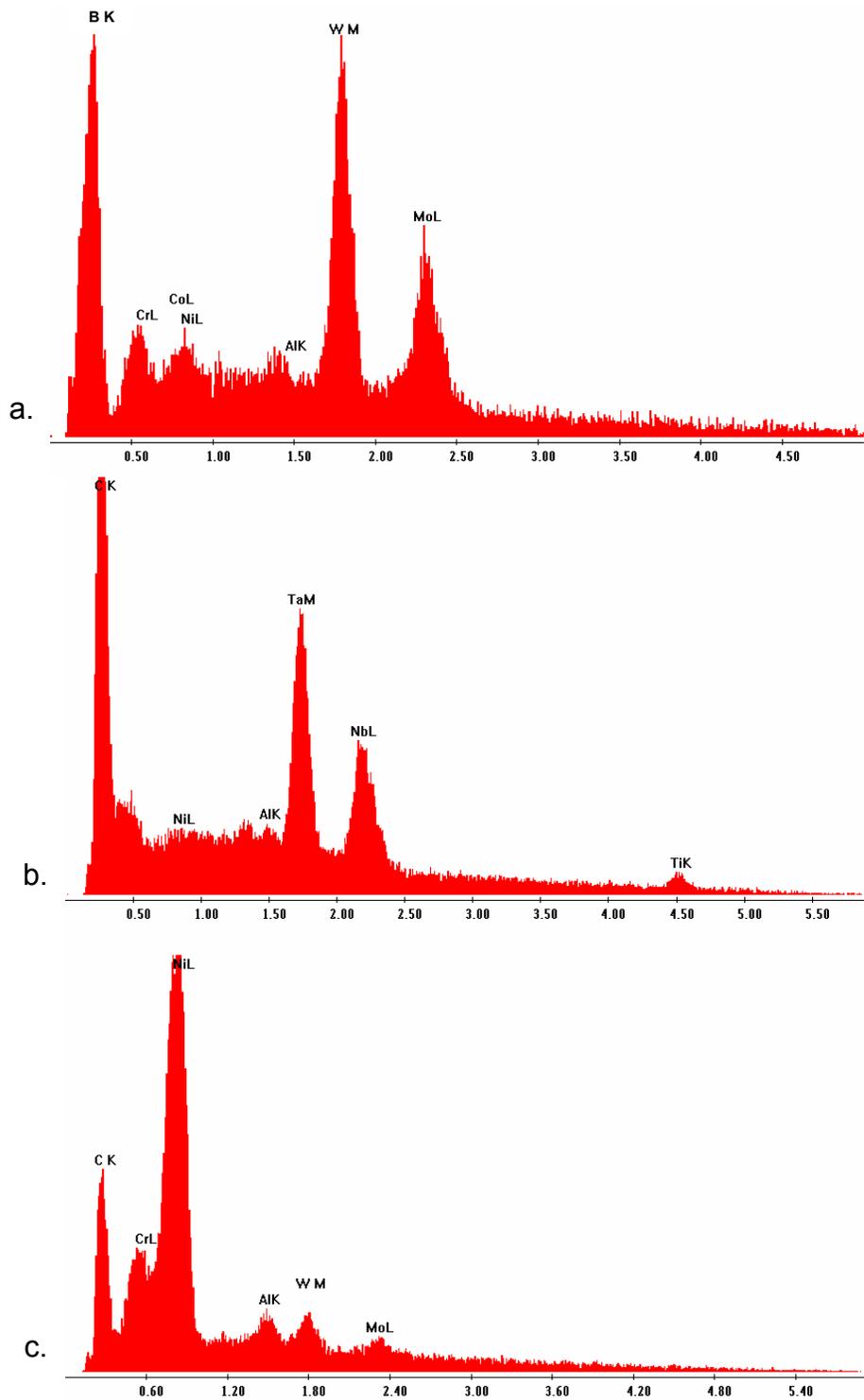


Figure 3.—Energy dispersive x-ray spectra showing carbides:  
 a.  $(W,Mo,Cr)_3B_2$  b.  $(Ta,Nb,Ti)C$ , c.  $(W,Cr)_{23}C_6$ .

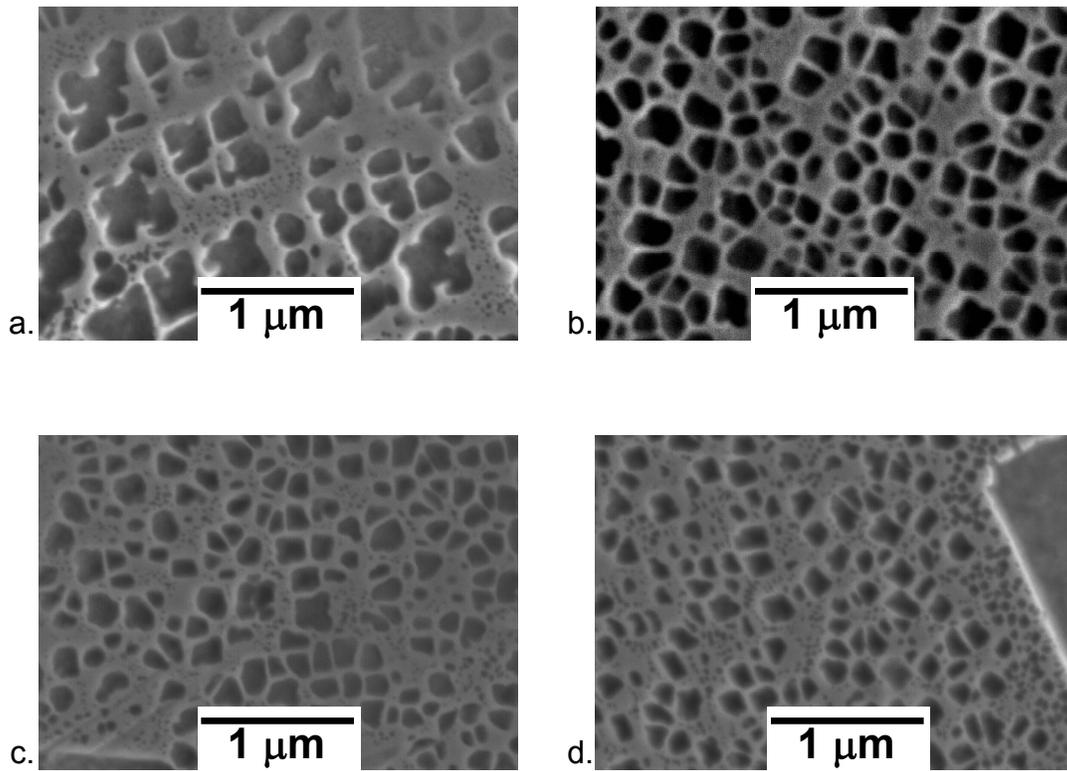


Figure 4.—FESEM micrographs of supersolvus and subsolvus disk  $\gamma'$  microstructures:  
a. supersolvus bore, b. supersolvus rim, c. subsolvus bore, d. subsolvus rim.

### Thermal Diffusivity $\alpha$

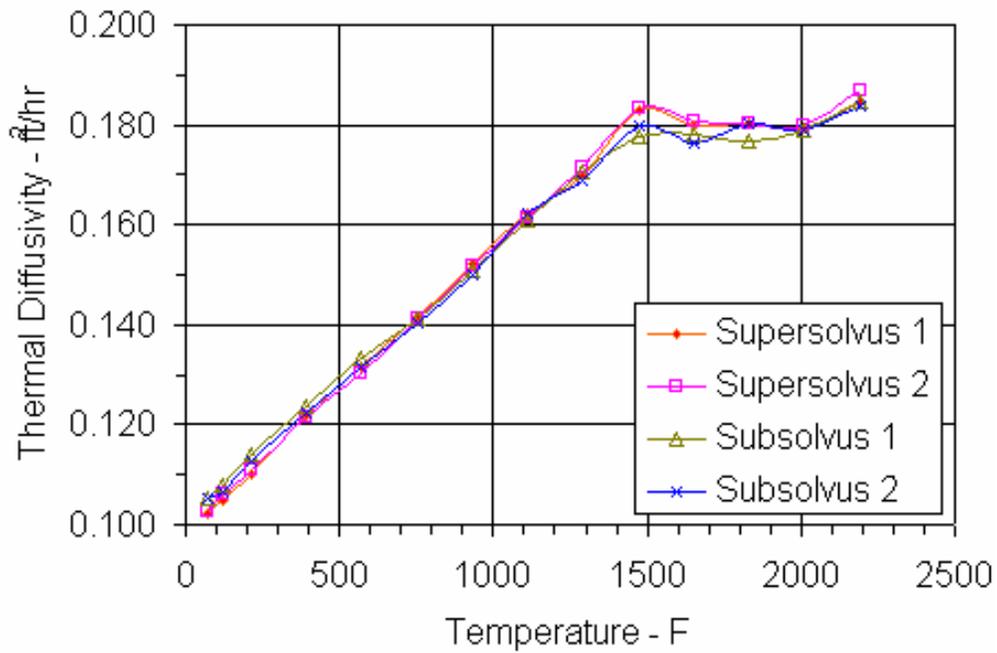
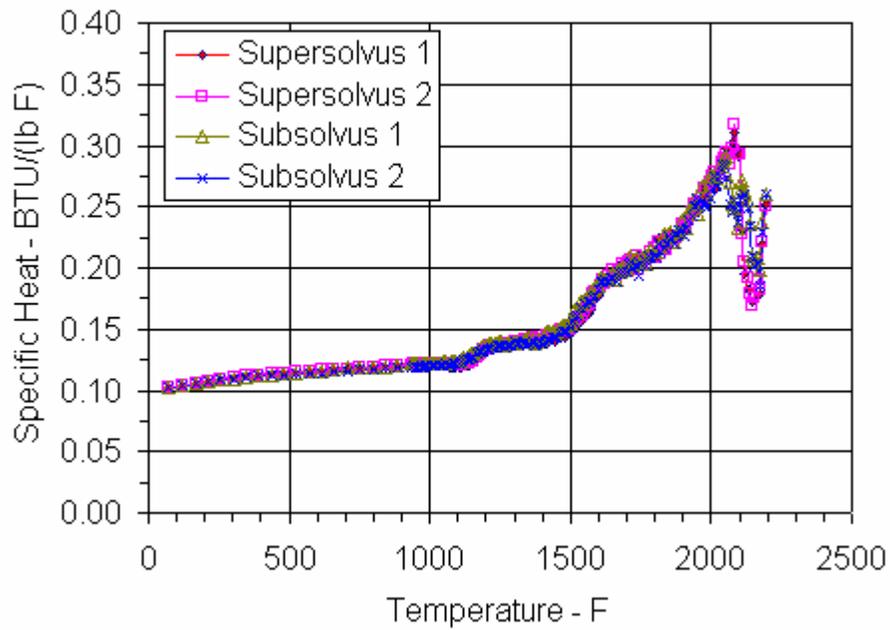


Figure 5.—Thermal diffusivity vs. temperature in supersolvus and subsolvus material.

Specific Heat  $C_p$  (Heating data)



Specific Heat  $C_p$  (Cooling data)

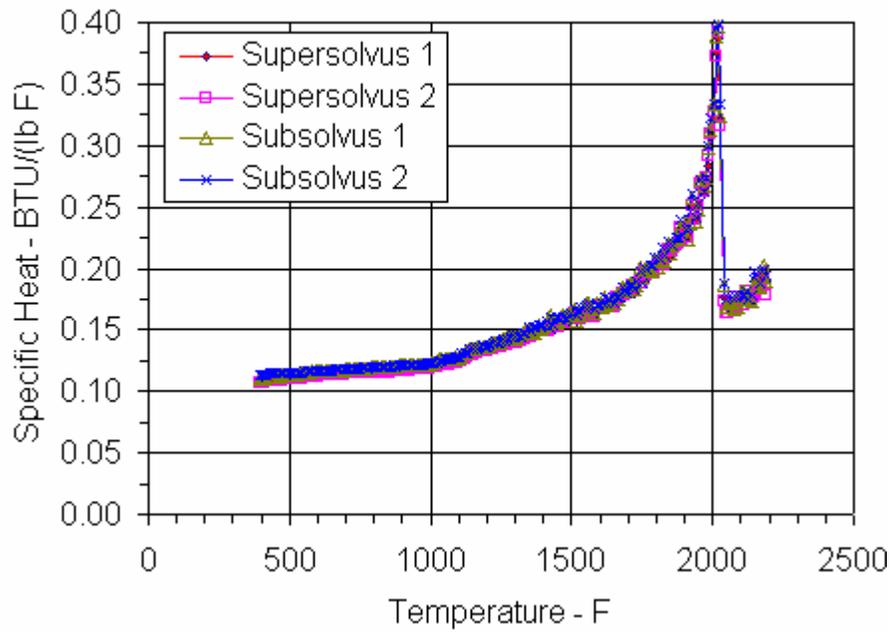


Figure 6.—Specific heat vs. temperature of supersolvus and subsolvus material during a. heating and b. cooling.

### Thermal Conductivity $\lambda$

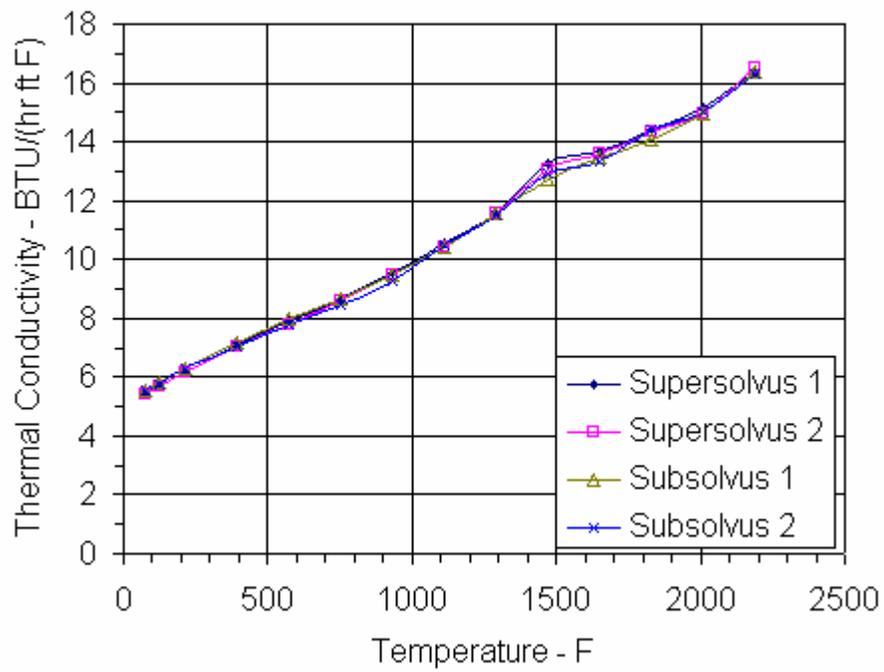
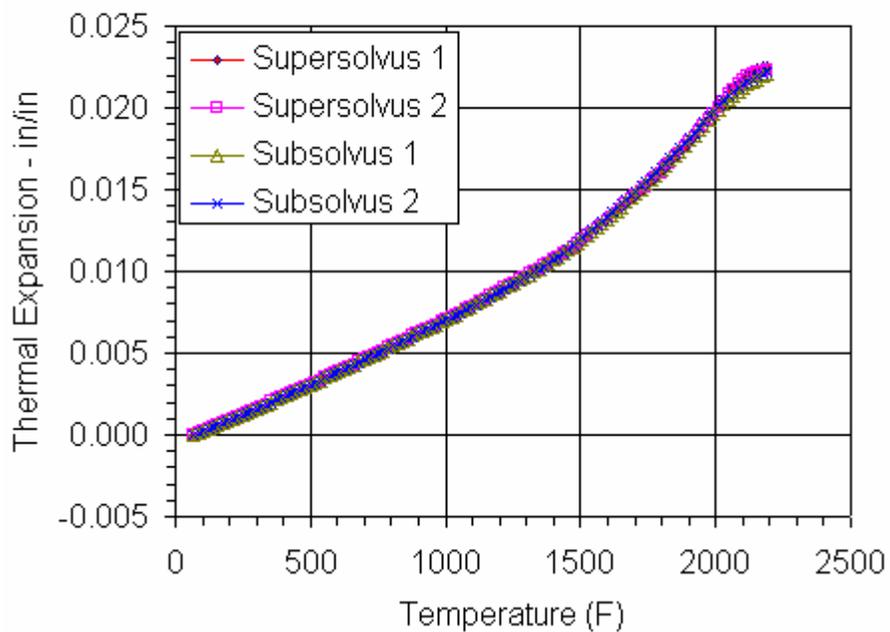


Figure 7.—Thermal conductivity vs. temperature of supersolvus and subsolvus material.

Thermal Expansion  $(L-L_0)/L_0$  (Heating data)



Thermal Expansion  $(L-L_0)/L_0$  (Cooling data)

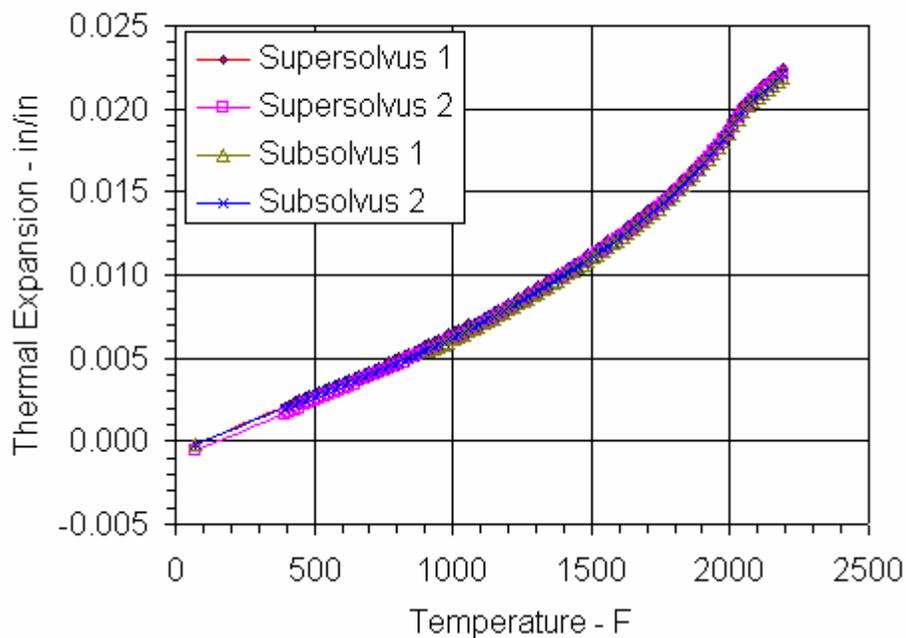
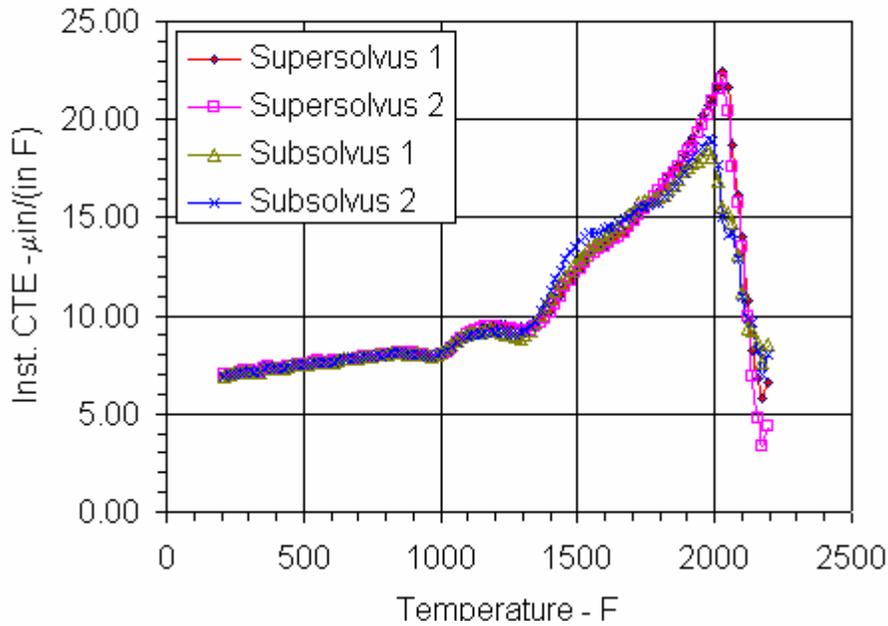


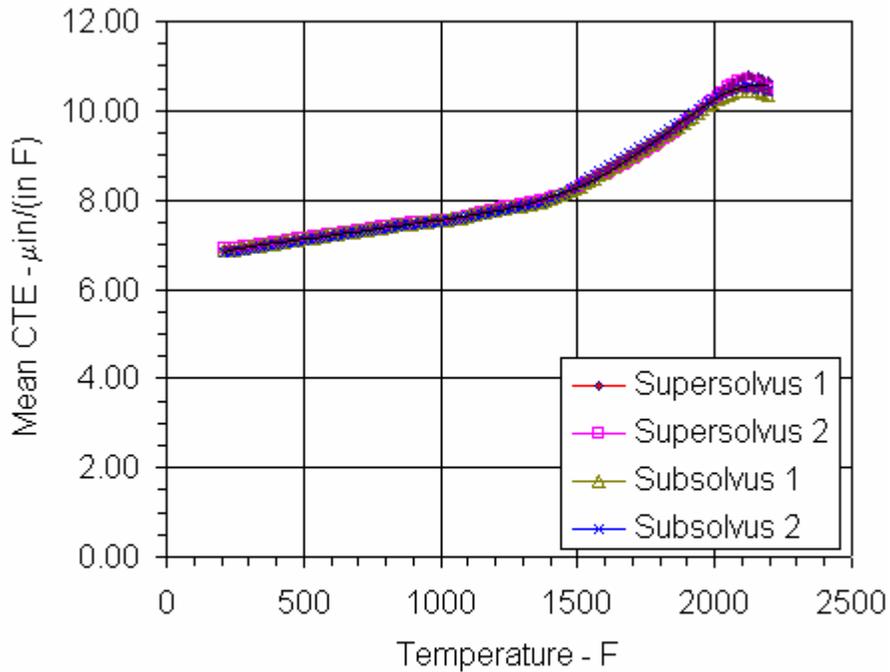
Figure 8.—Thermal expansion vs. temperature of supersolvus and subsolvus material during a. heating and b. cooling.

Instantaneous Coefficient of Thermal Expansion  
CTE



c

Mean Coefficient of Thermal Expansion CTE



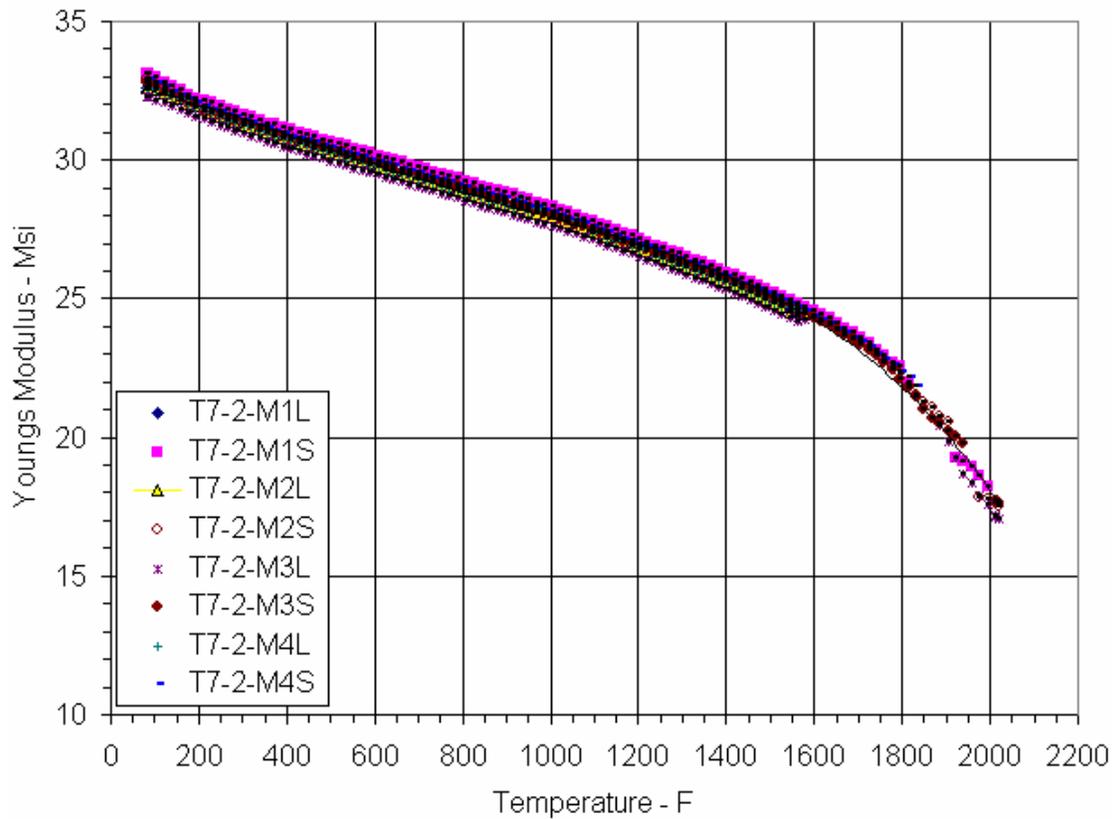
$$\text{CTE} = -1.3509\text{E-}18\text{T}^6 + 8.0125\text{E-}15\text{T}^5 - 1.7964\text{E-}11\text{T}^4 + 1.9931\text{E-}8\text{T}^3 - 1.1626\text{E-}5\text{T}^2 + 4.2380\text{E-}3\text{T} + 6.3117$$

$$R^2 = .998$$

d.

Figure 8.—c. Instantaneous and d. mean coefficient of thermal expansion vs. temperature of supersolvus and subsolvus material.

Youngs Modulus vs. Temperature



$$E = -2.3627E-12T^4 + 6.6246E-9T^3 - 5.7637E-6T^2 - 3.4502E-3T + 32.859$$
$$R^2 = .994$$

Figure 9.—Young's modulus vs. temperature for supersolvus material.

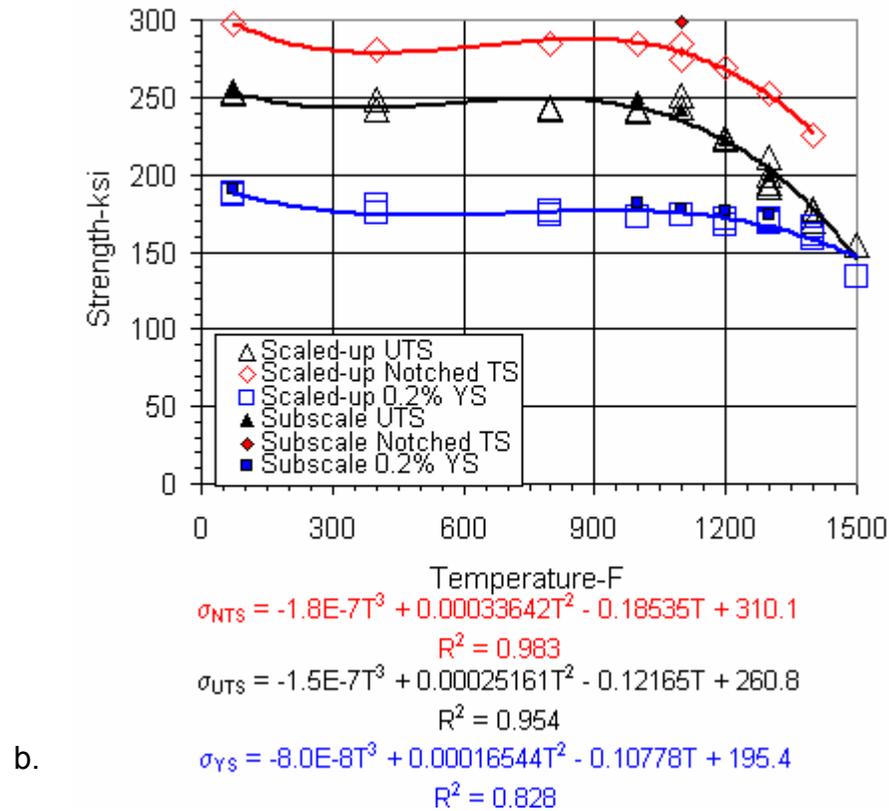
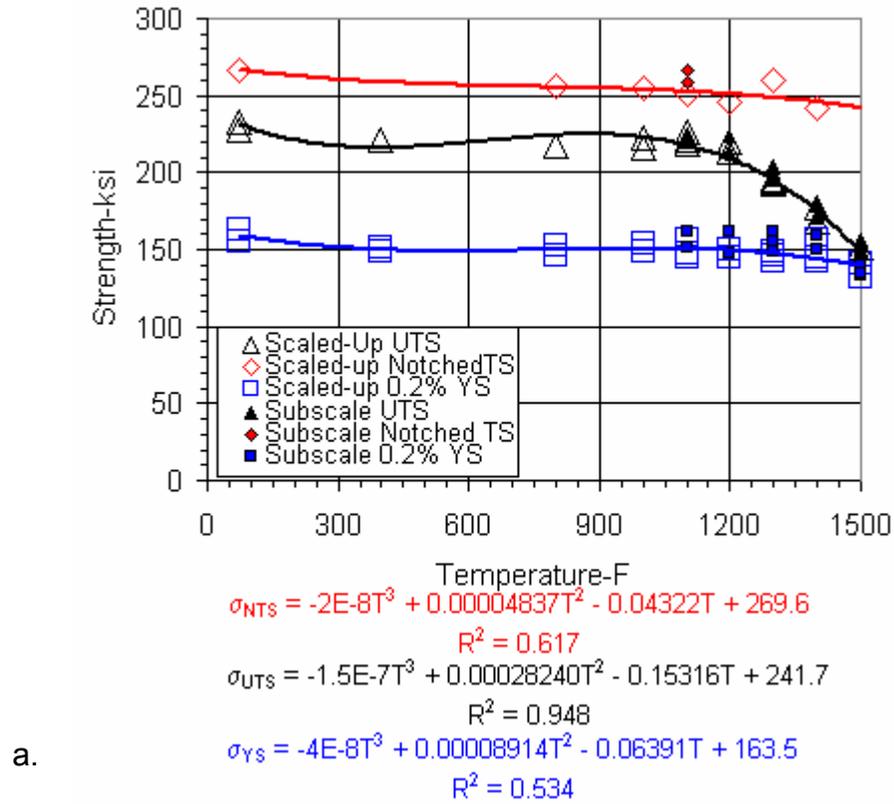
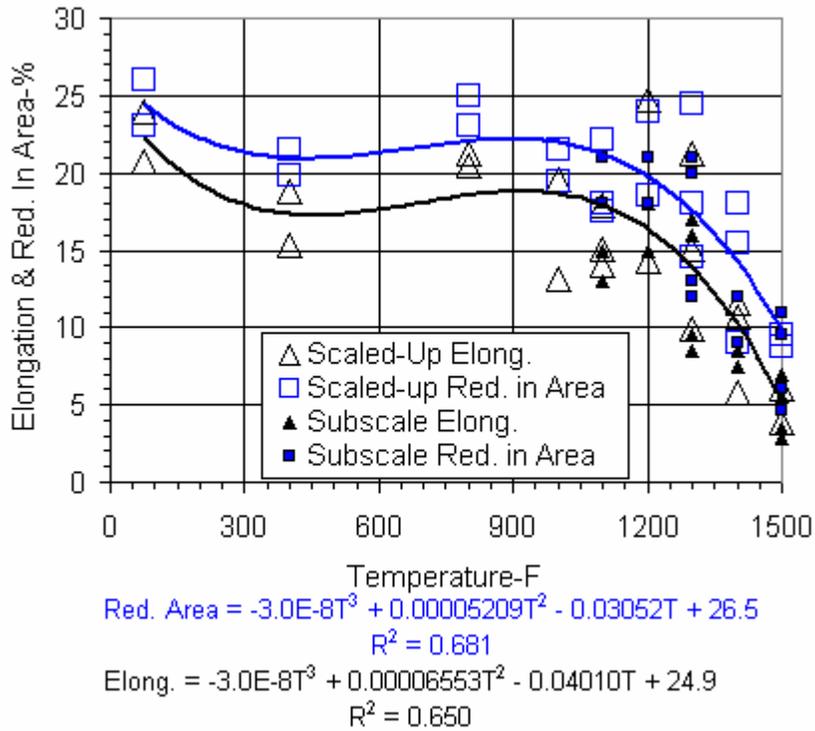
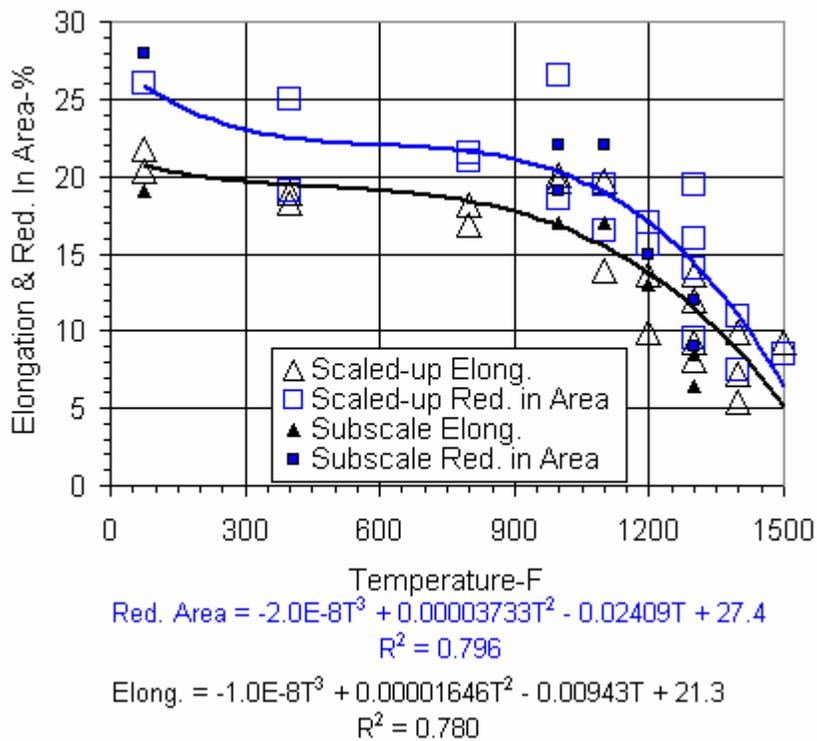


Figure 10.—0.2 percent yield strength, ultimate strength, and notched tensile strength of a. supersolvus and b. subsolvus material.

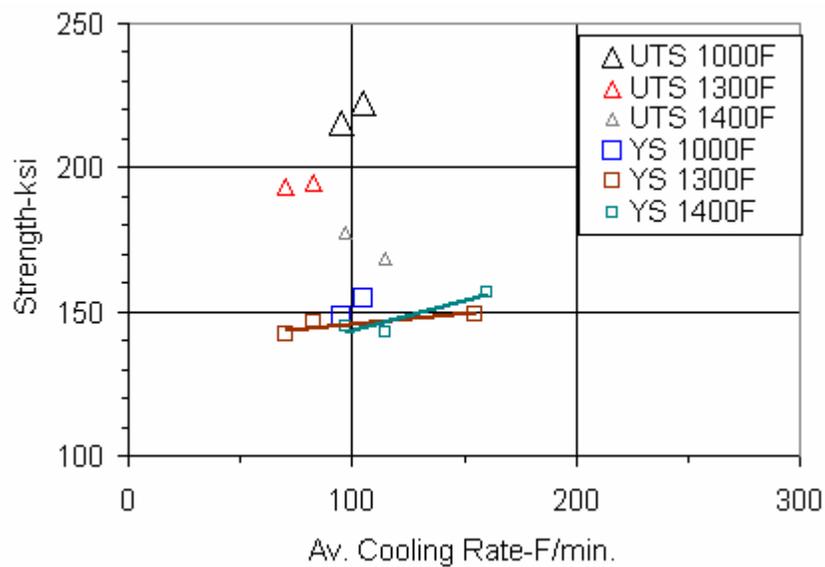


a.

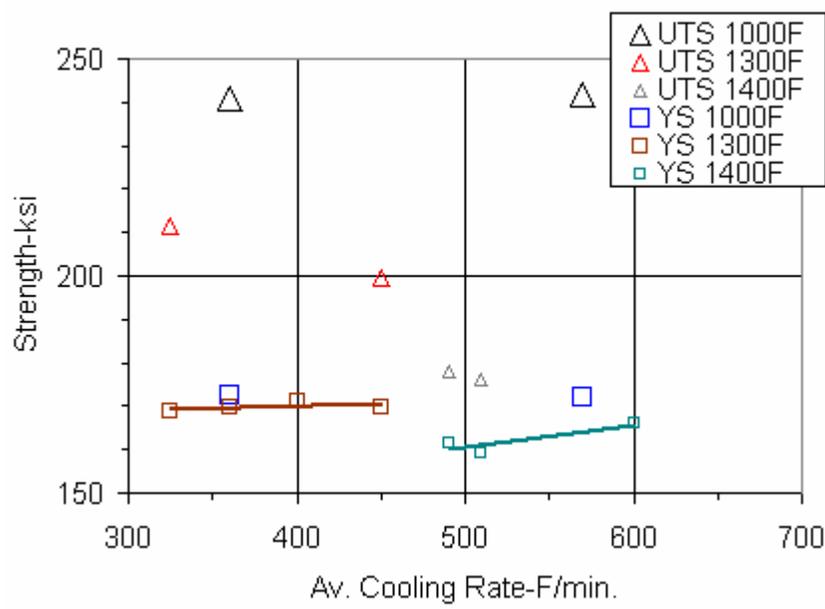


b.

Figure 11.—Elongation and reduction in area of tensile tests for a. supersolvus and b. subsolvus material.

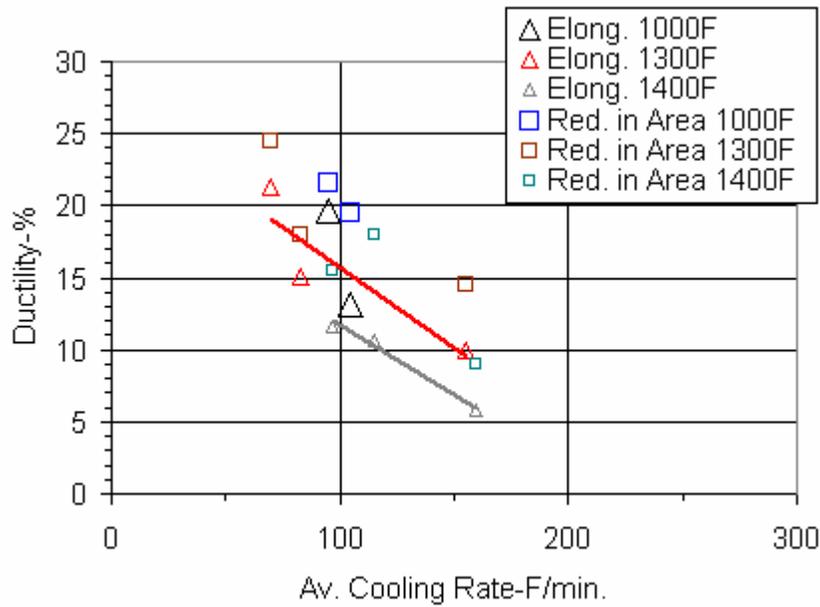


a.

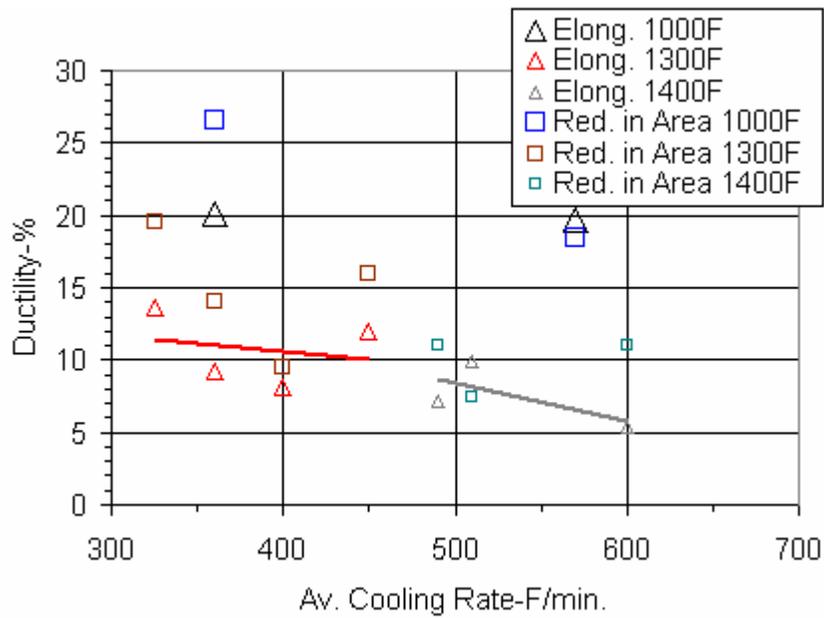


b.

Figure 12.—Yield and ultimate strengths vs. average cooling rate of tensile tests for a. supersolvus and b. subsolvus scaled-up material.



a.



b.

Figure 13.—Elongation and reduction in area vs. average cooling rate of tensile tests for a. supersolvus and b. subsolvus scaled-up material.

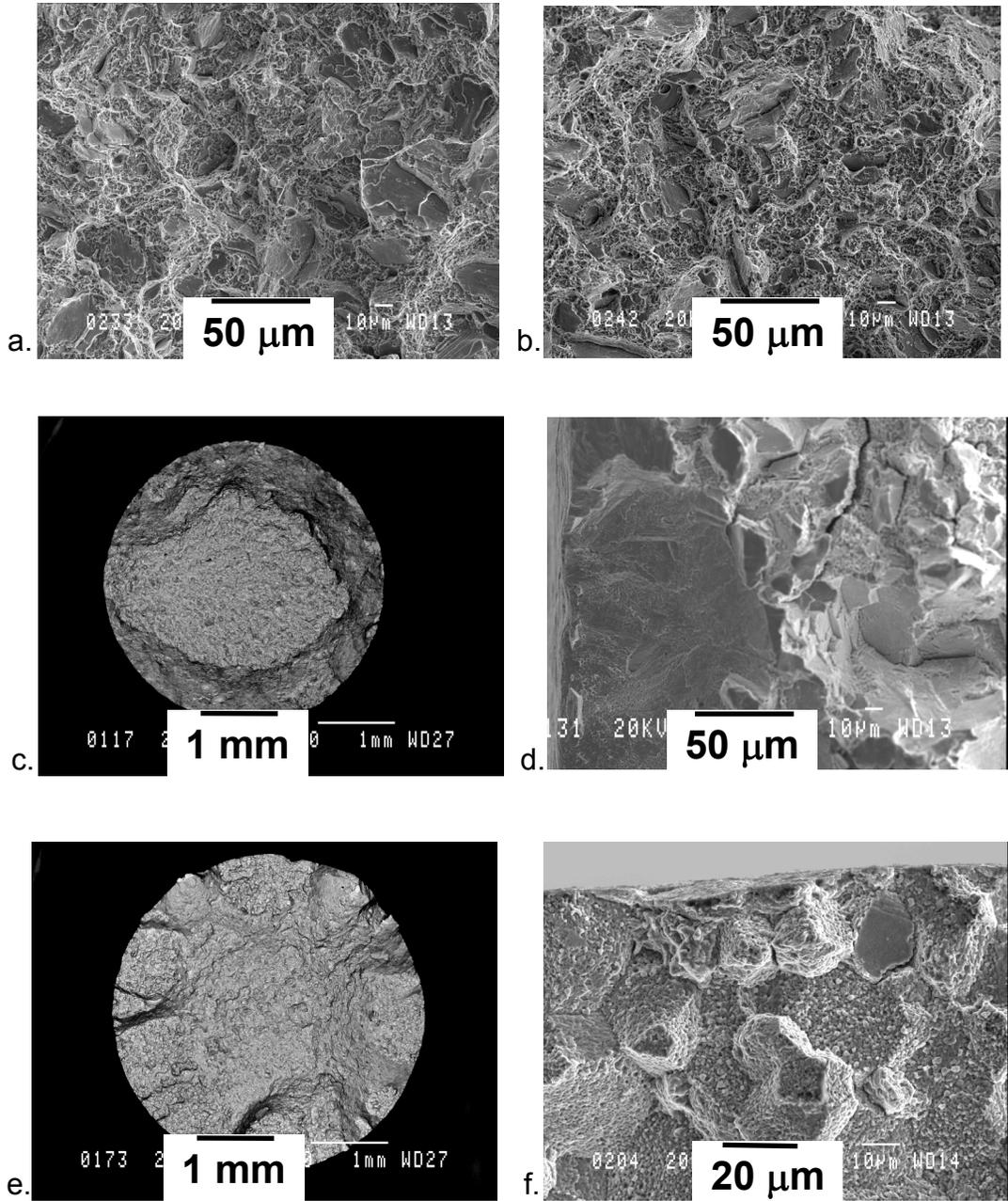


Figure 14.—Fracture surfaces observed for supersolvus tensile specimens tested at a. 75 °F, b. 800 °F, c. and d. 1300 °F, e. and f. 1500 °F.

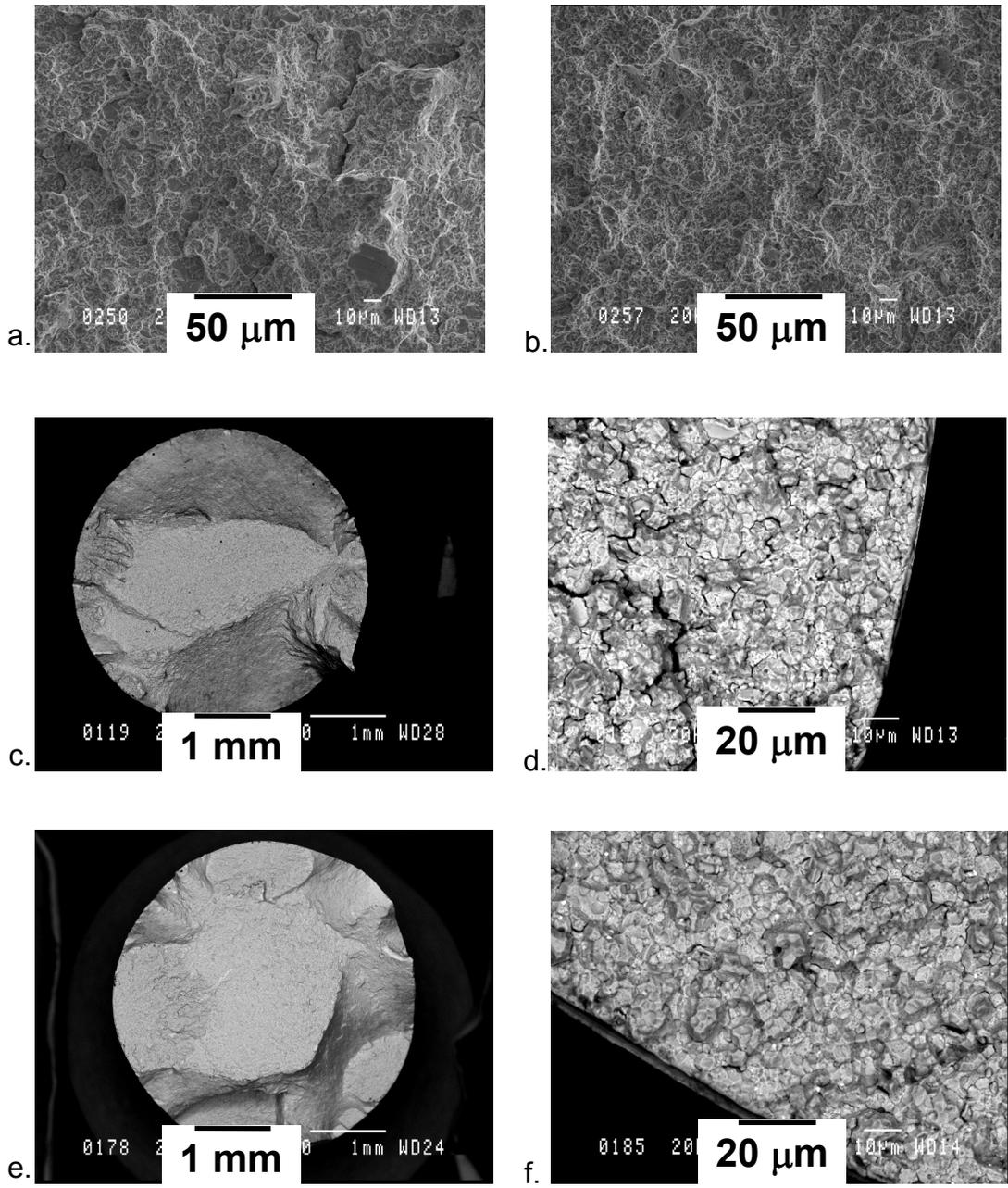
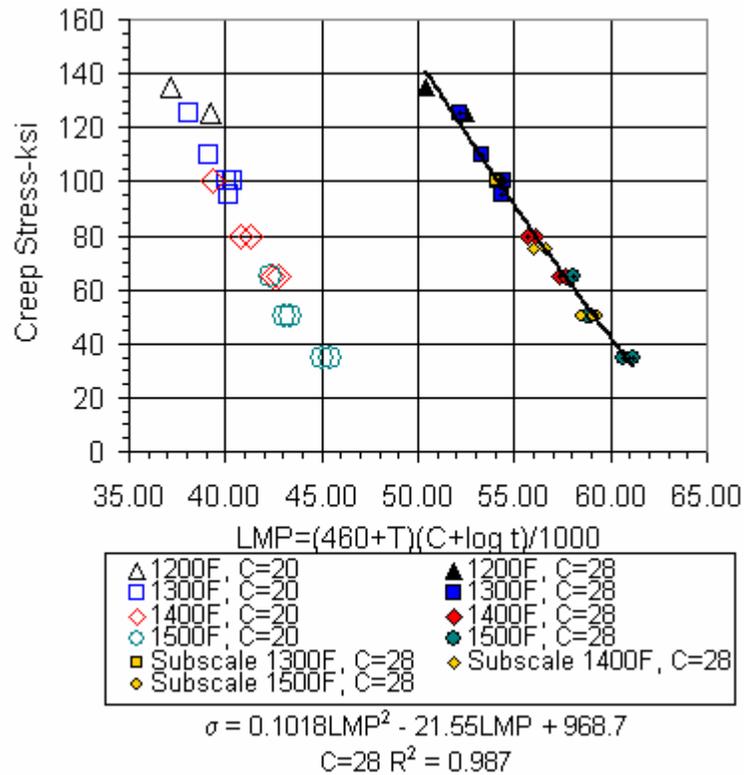
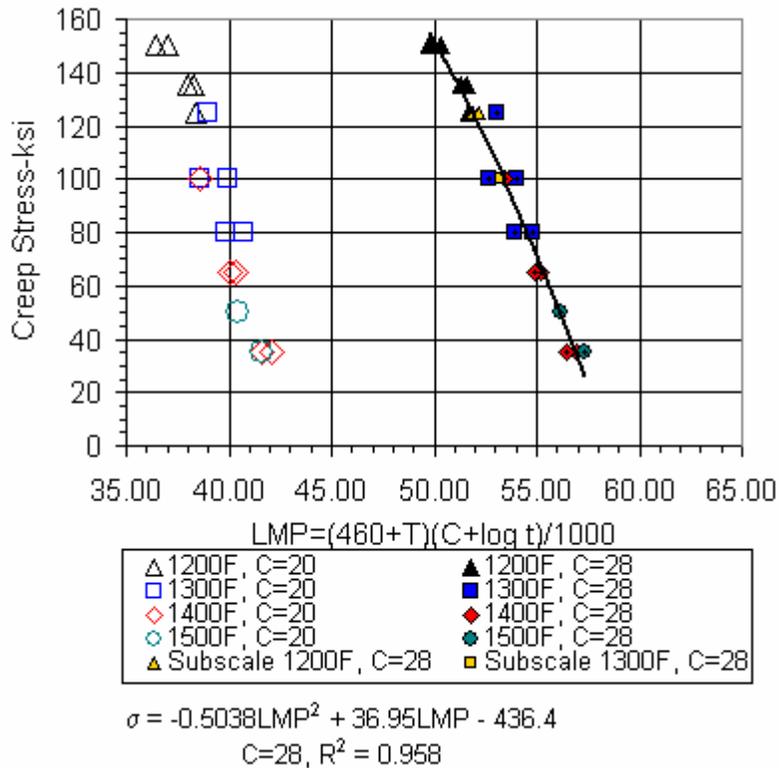


Figure 15.—Fracture surfaces observed for subsolvus tensile specimens tested at a. 75 °F, b. 800 °F, c. and d. 1300 °F, e. and f. 1500 °F.

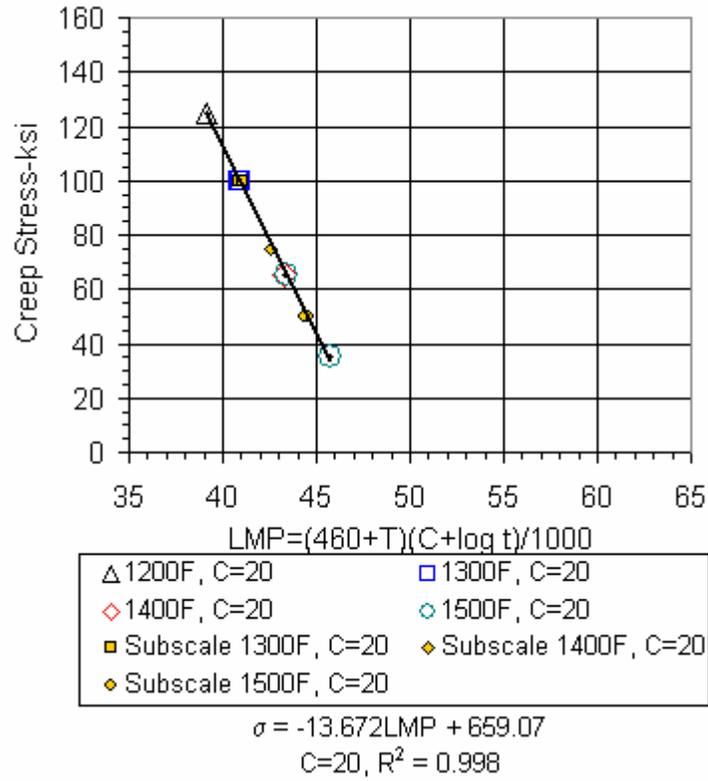


a.

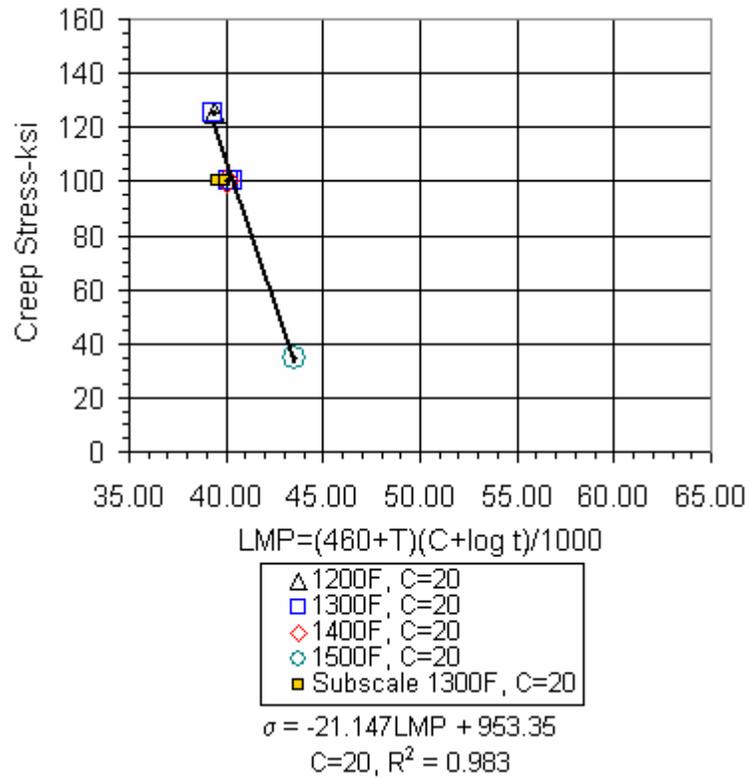


b.

Figure 16.—0.2% creep lives expressed using Larson-Miller parameters for a. supersolvus and b. subsolvus material.



a.



b.

Figure 17.—Rupture lives expressed using Larson-Miller parameters for a. supersolvus and b. subsolvus material.

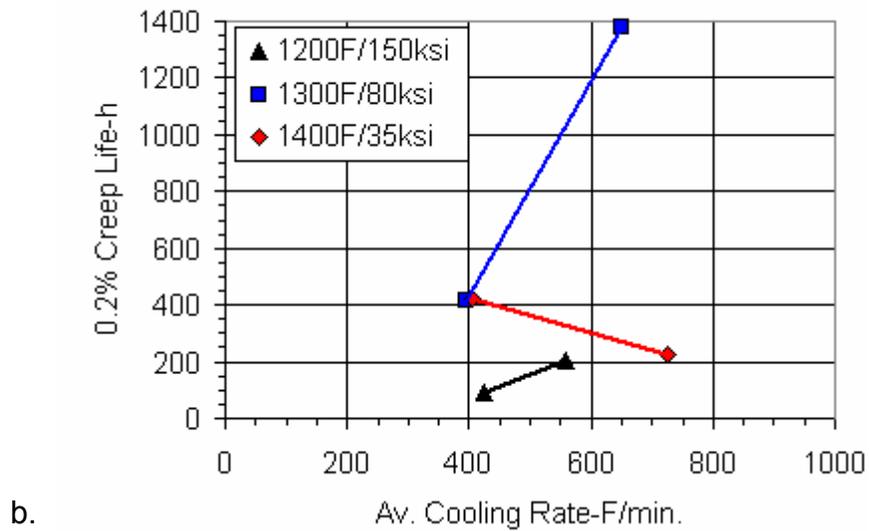
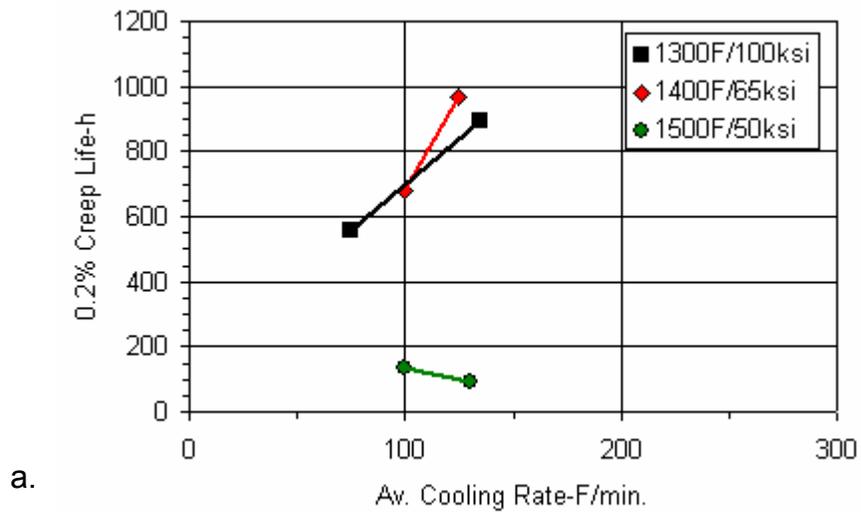


Figure 18.—0.2% creep lives vs. average cooling rate for  
 a. supersolvus and b. subsolvus material.

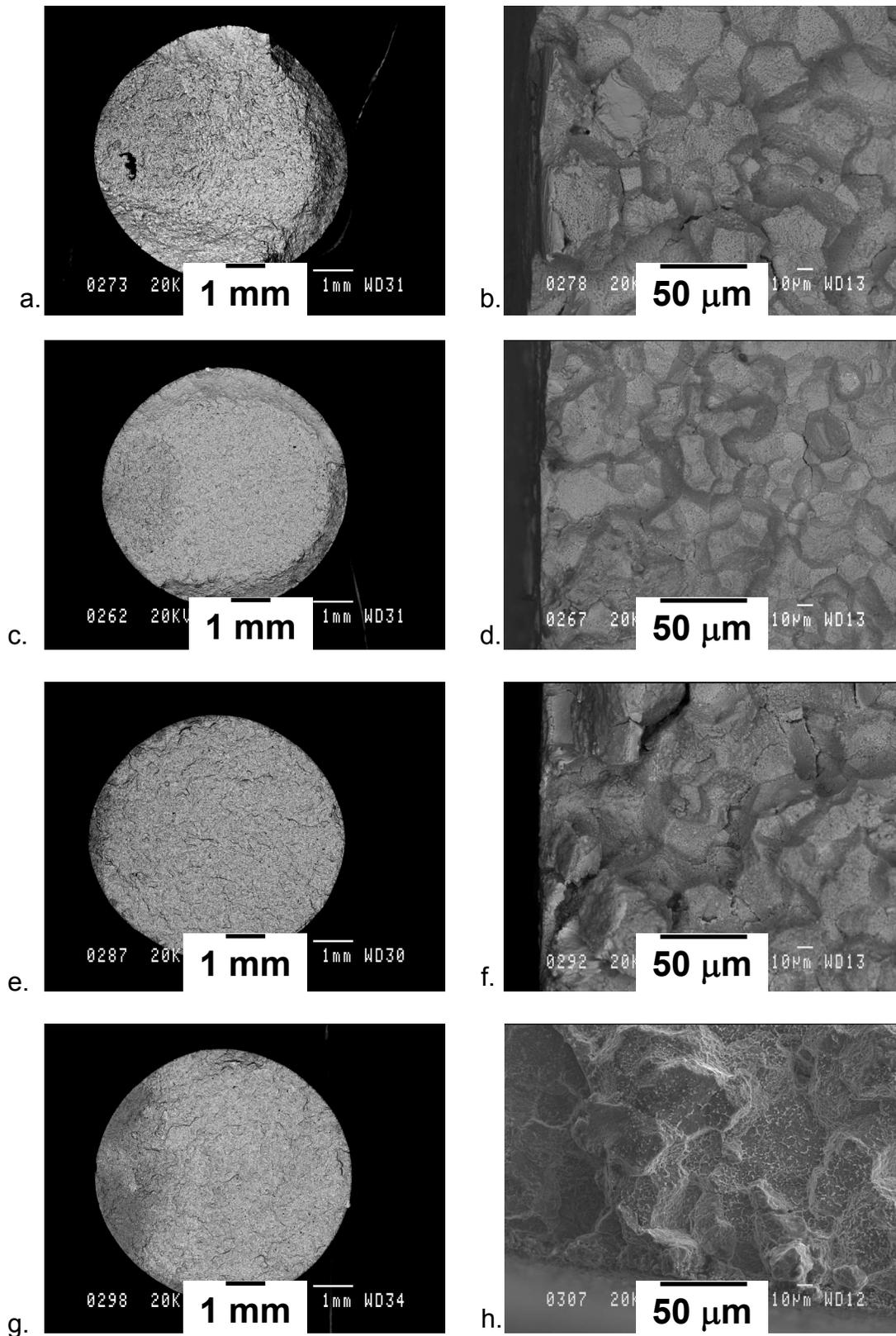


Figure 19.—Fracture surfaces observed for supersolvus creep specimens tested at a. and b. 1200 °F/125 ksi, c. and d. 1300 °F/100 ksi, e. and f. 1400 °F/65 ksi, g. and h. 1500 °F/50 ksi.

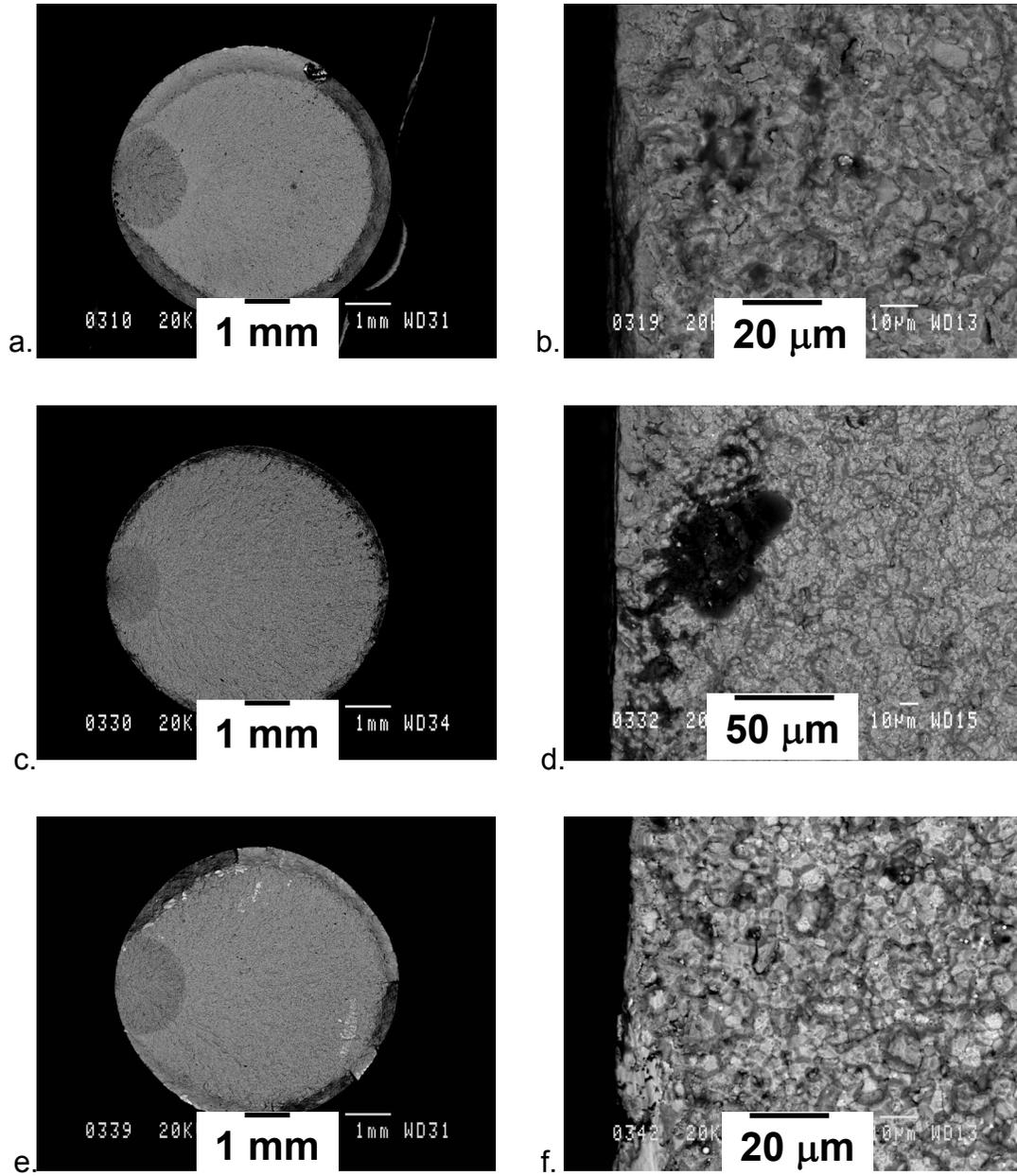


Figure 20.—Fracture surfaces observed for sub-solvus creep specimens tested at a. and b. 1200 °F/125 ksi, c. and d. 1300 °F/100 ksi, e. and f. 1400 °F/65 ksi.

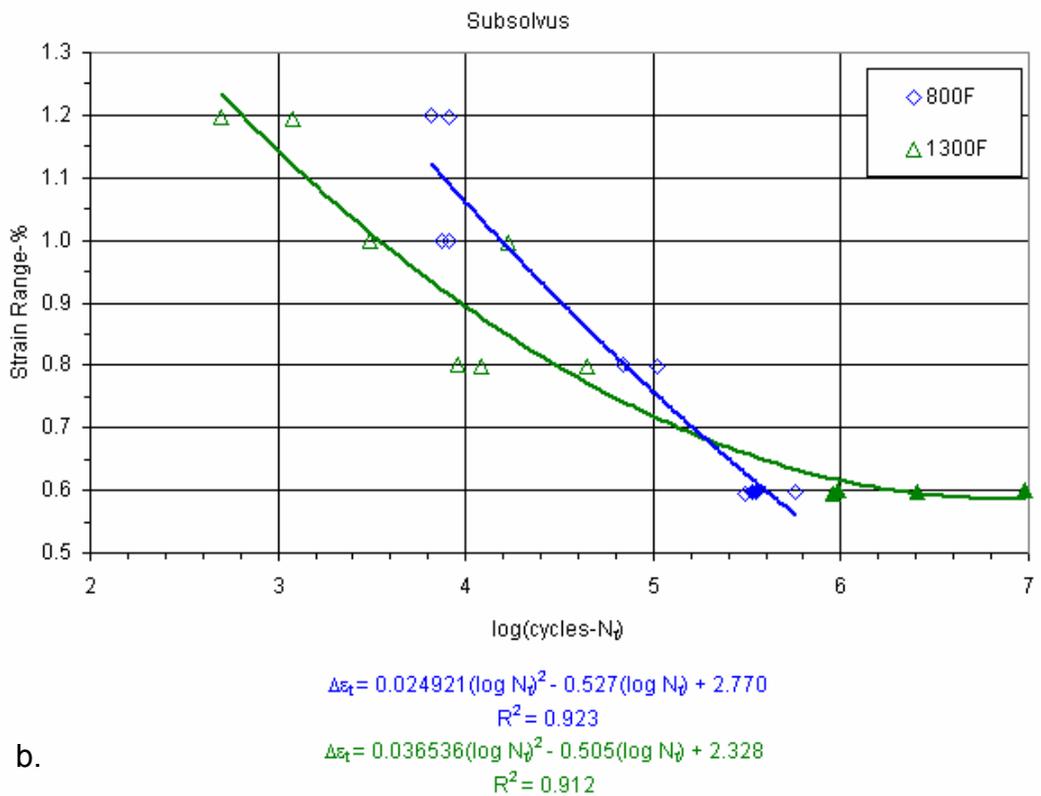
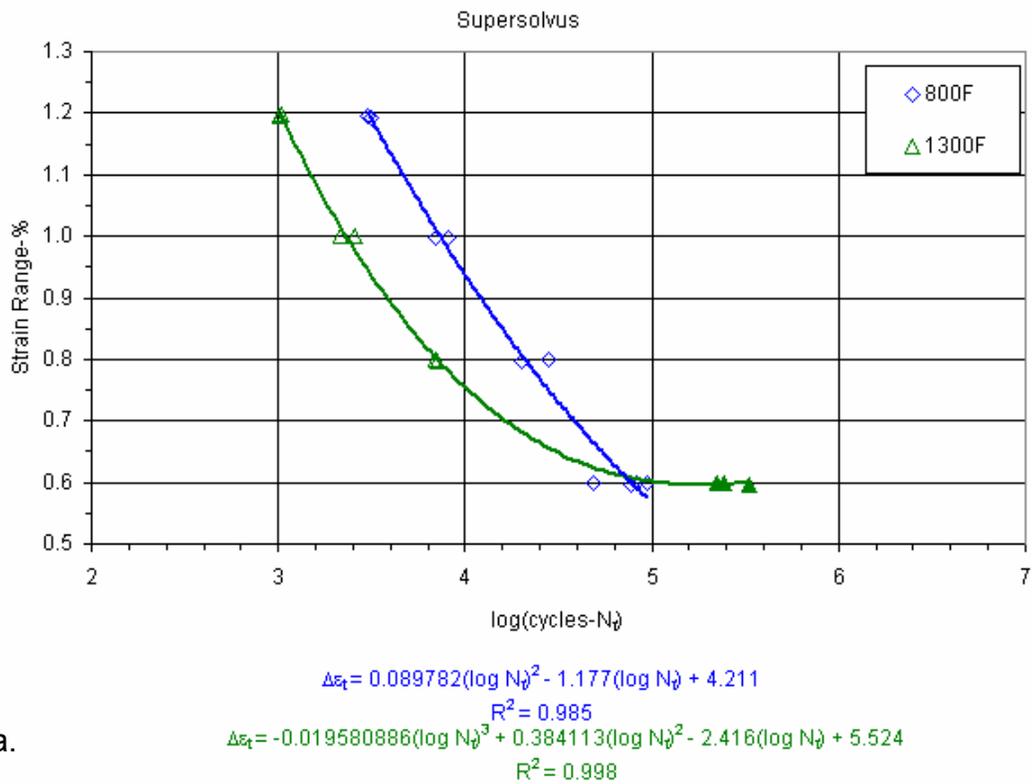


Figure 21.—Fatigue lives vs. strain range for a. supersolvus and b. subsolvus material. Open symbols=surface-initiated failures, filled symbols=internal-initiated failures.

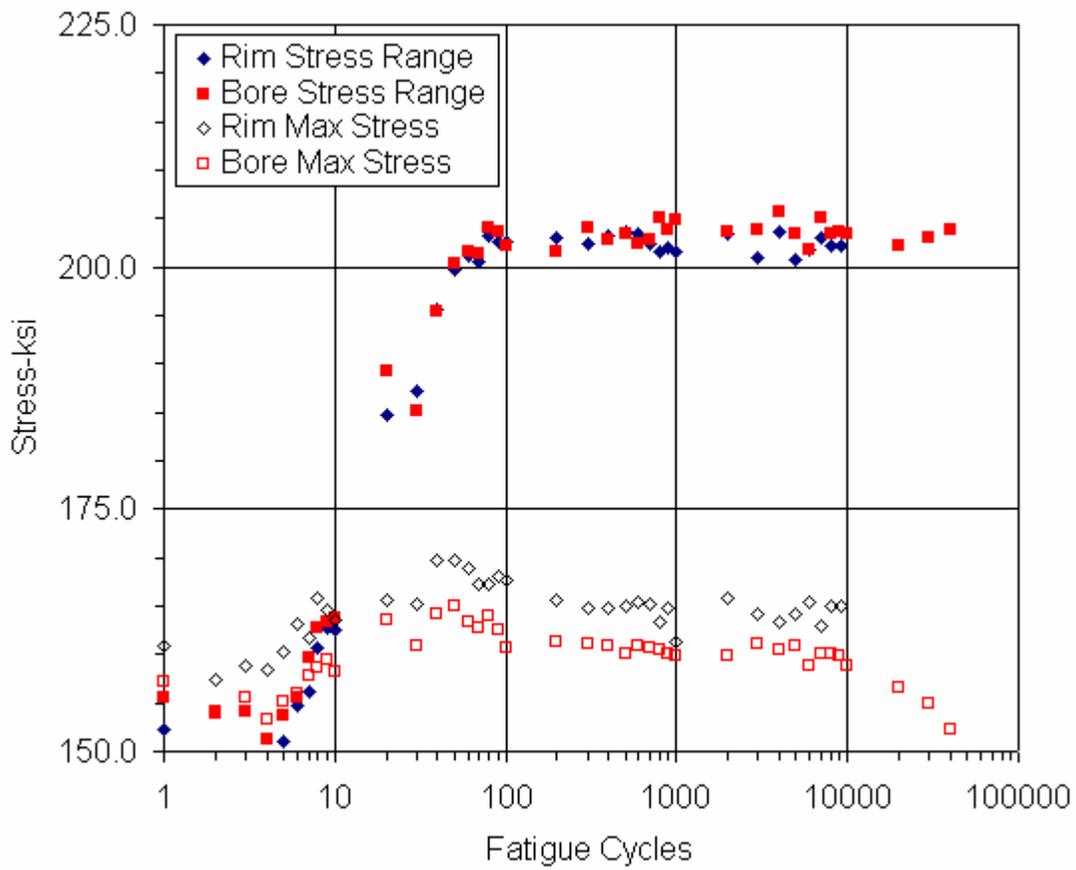


Figure 22.—Maximum stress and stress range as functions of cycles for subsolvus rim and bore specimens both tested at a total strain range of 0.8% and 1300 °F.

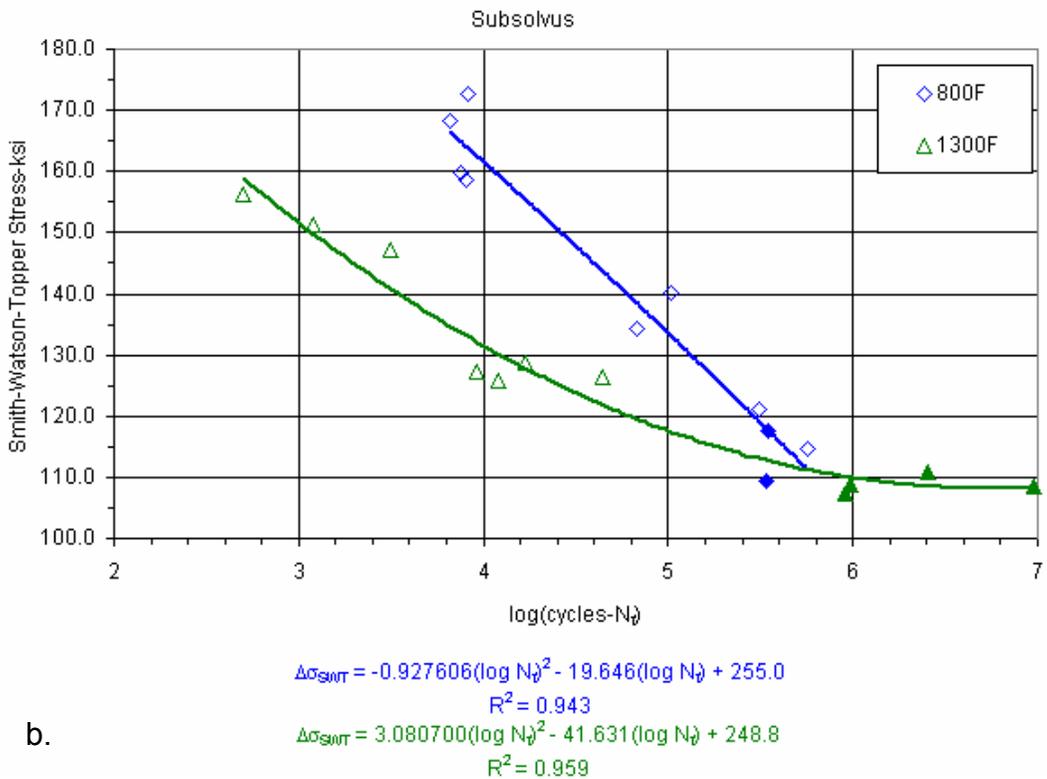
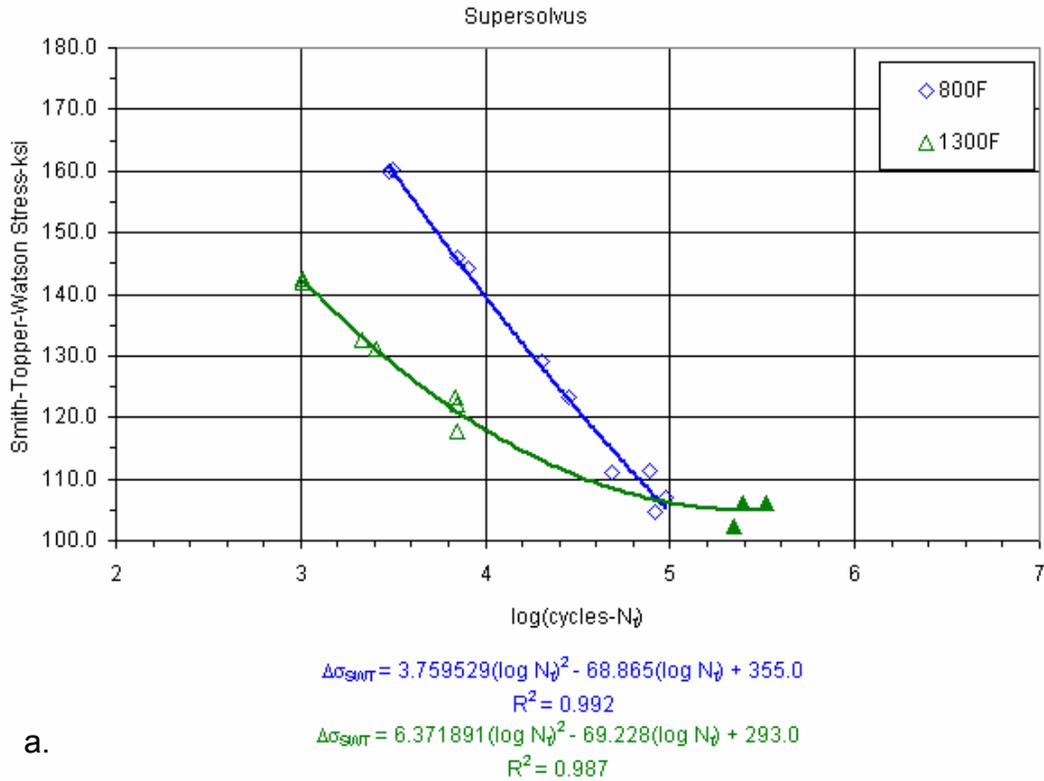


Figure 23.—Fatigue lives vs. Smith-Watson-Topper stress for a. supersolvus and b. subsolvus material. Open symbols=surface-initiated failures, filled symbols=internal-initiated failures.

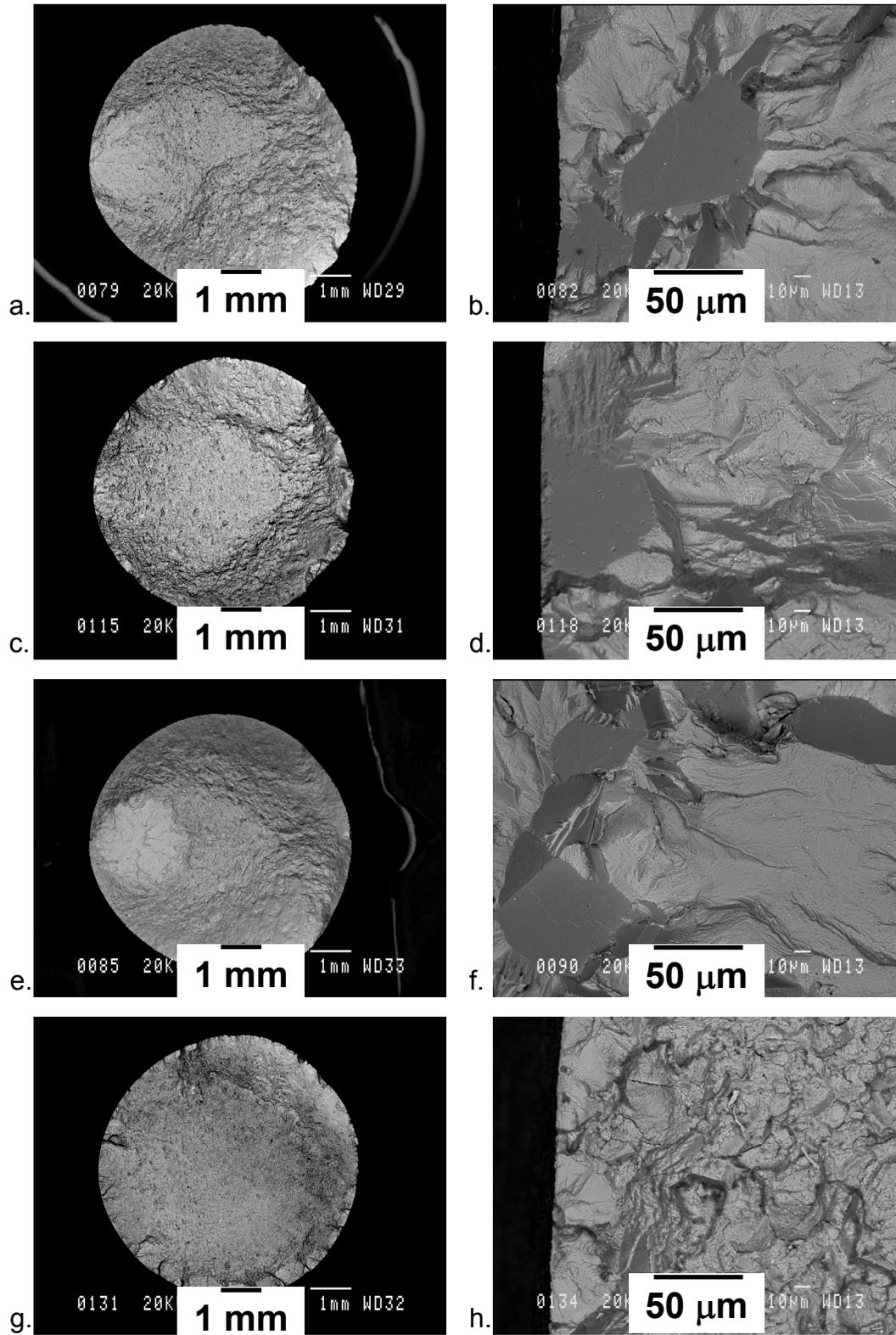


Figure 24.—Failure initiation sites observed for supersolvus LCF specimens tested at a. and b. 800 °F/0.6%, c. and d. 800 °F/1.2%, e. and f. 1300 °F/0.6%, g. and h. 1300 °F/1.2%.

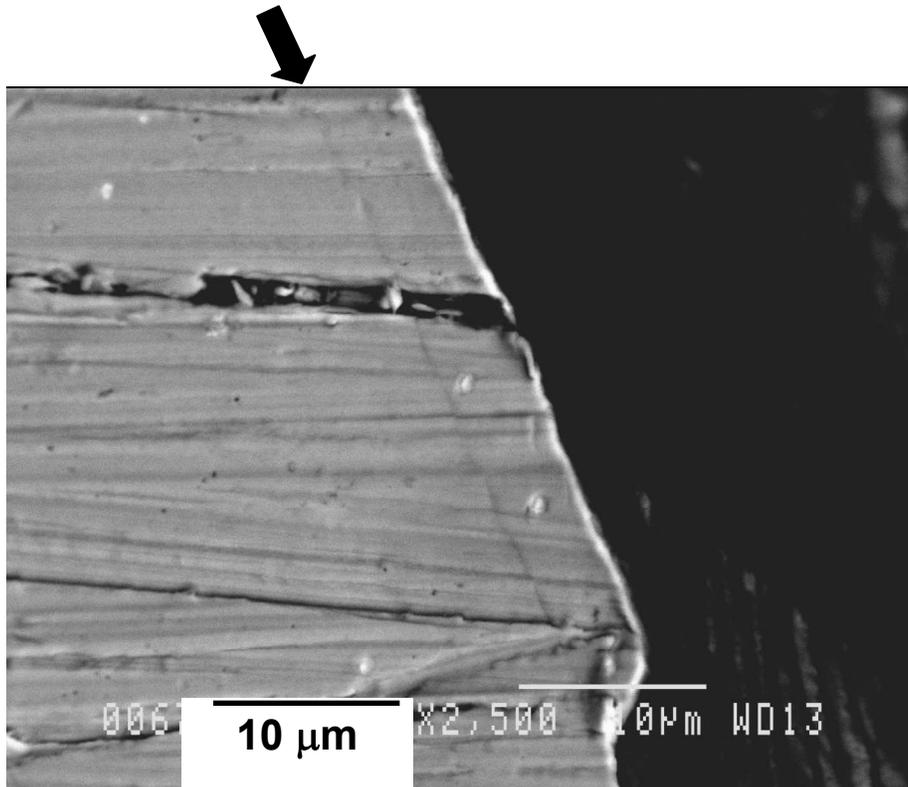


Figure 25.—Slip offset at arrow adjacent to grain facet initiated failure observed for supersolvus LCF specimen tested at 800 °F/0.8%.

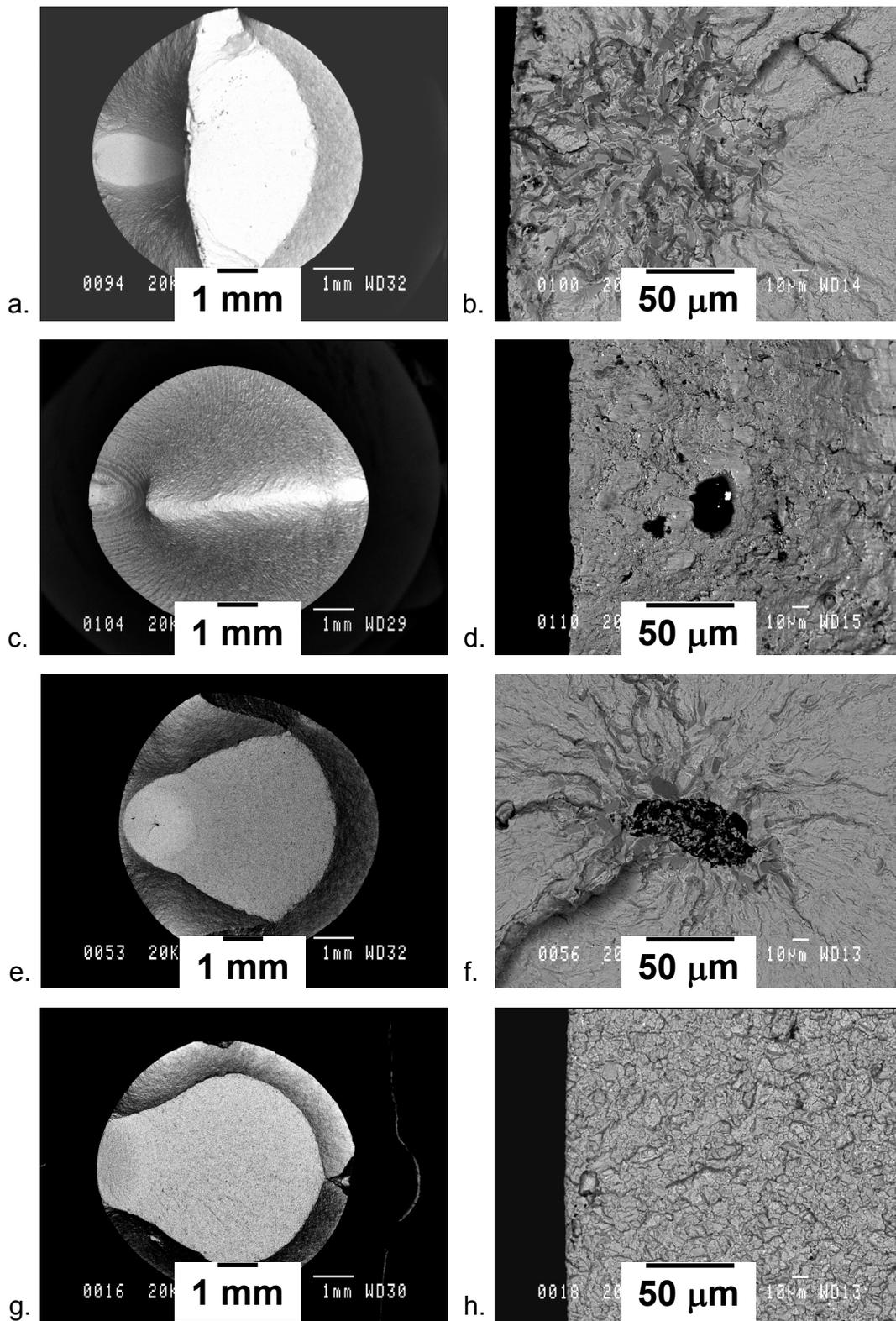
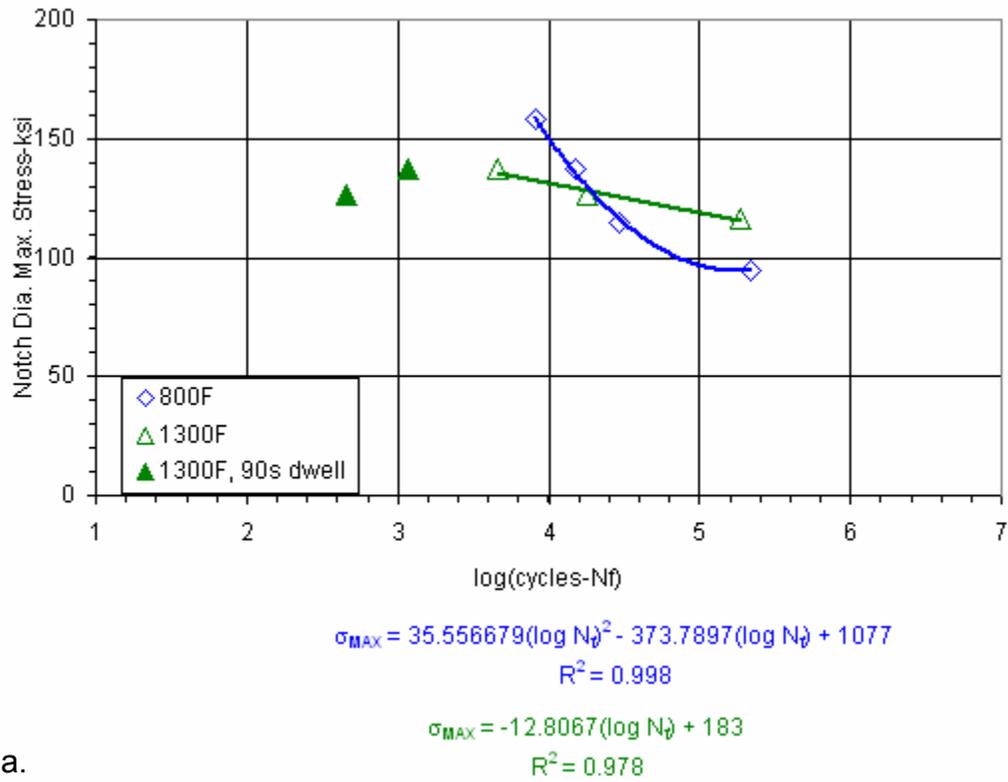
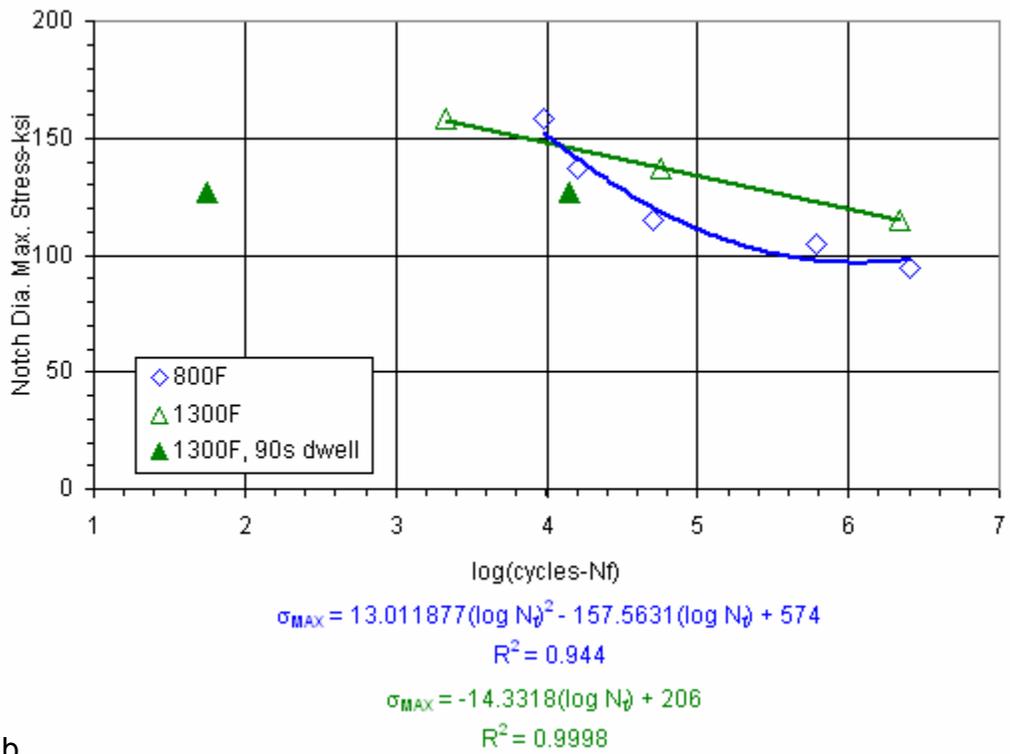


Figure 26.—Failure initiation sites observed for subsolvus LCF specimens tested at a. and b. 800 °F/0.6%, c. and d. 800 °F/1.2%, e. and f. 1300 °F/0.6%, g. and h. 1300 °F/1.2%.



a.



b.

Figure 27.—Fatigue lives vs. notch diameter maximum stress for a. supersolvus and b. subsolvus material.

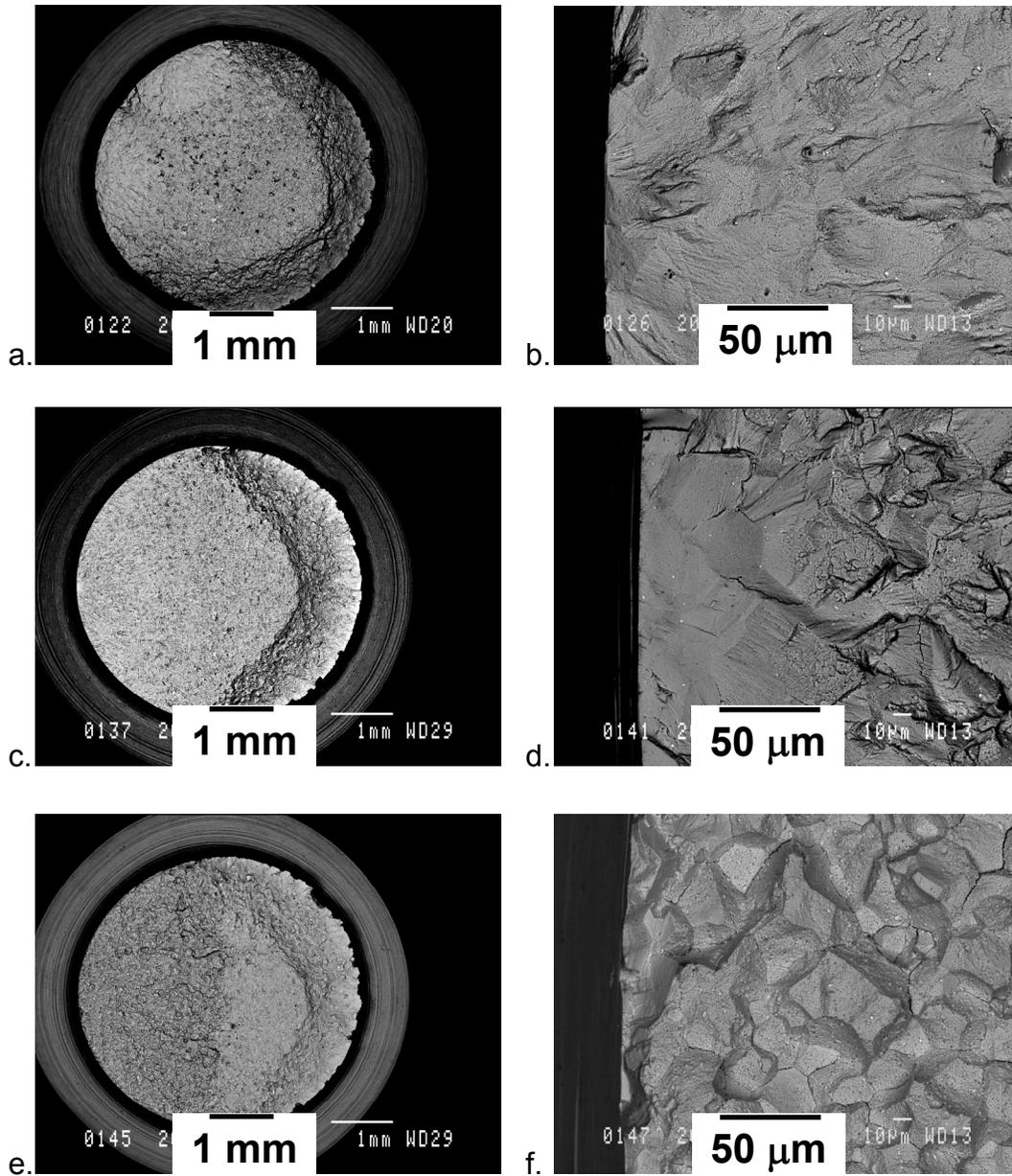


Figure 28.—Failure initiation sites observed for supersolvus notched LCF specimens tested at: a. and b. 800 °F/115 ksi maximum stress, c. and d. 1300 °F/127 ksi, e. and f. 1300 °F/127 ksi with superimposed 90 sec dwell.

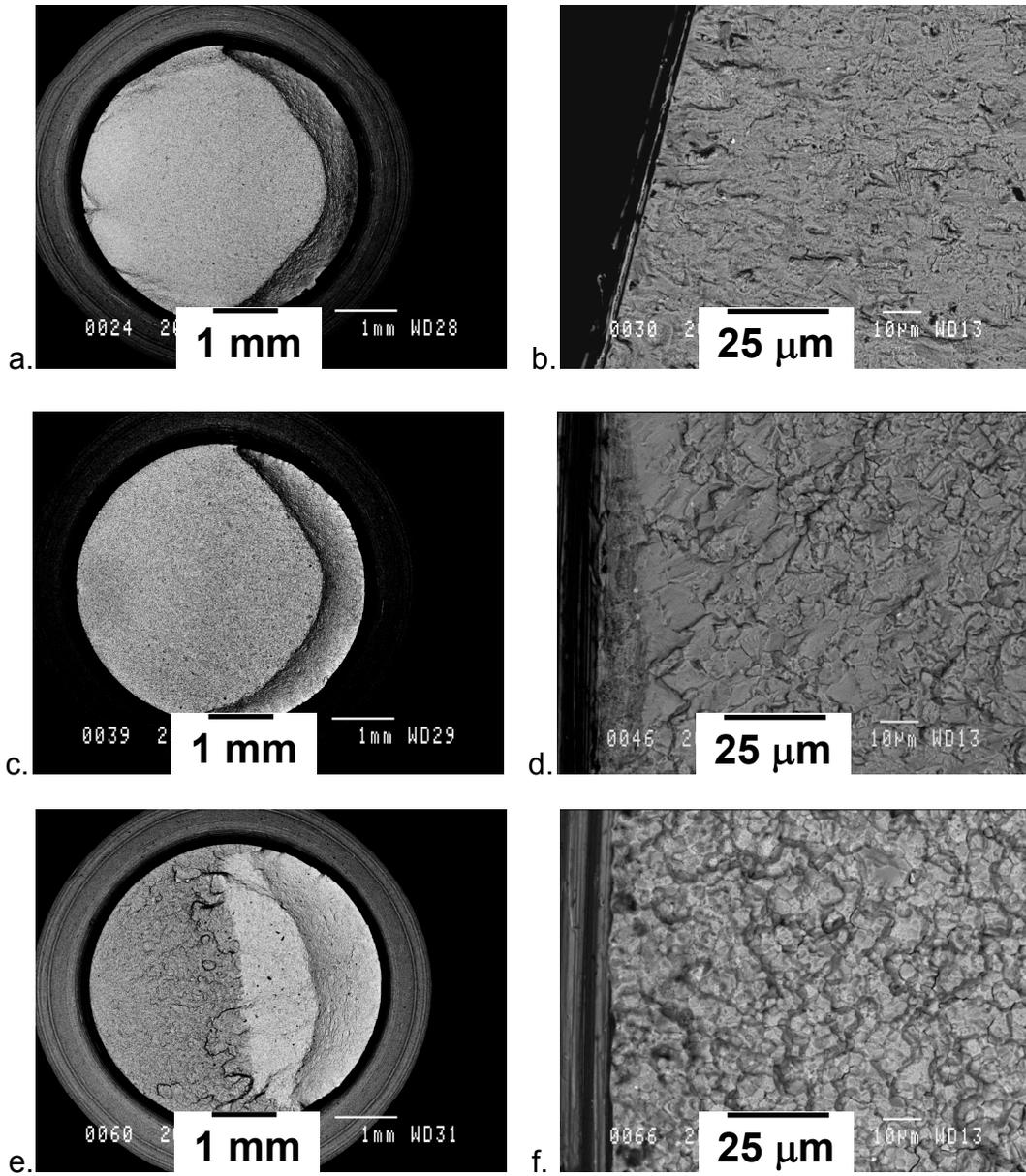
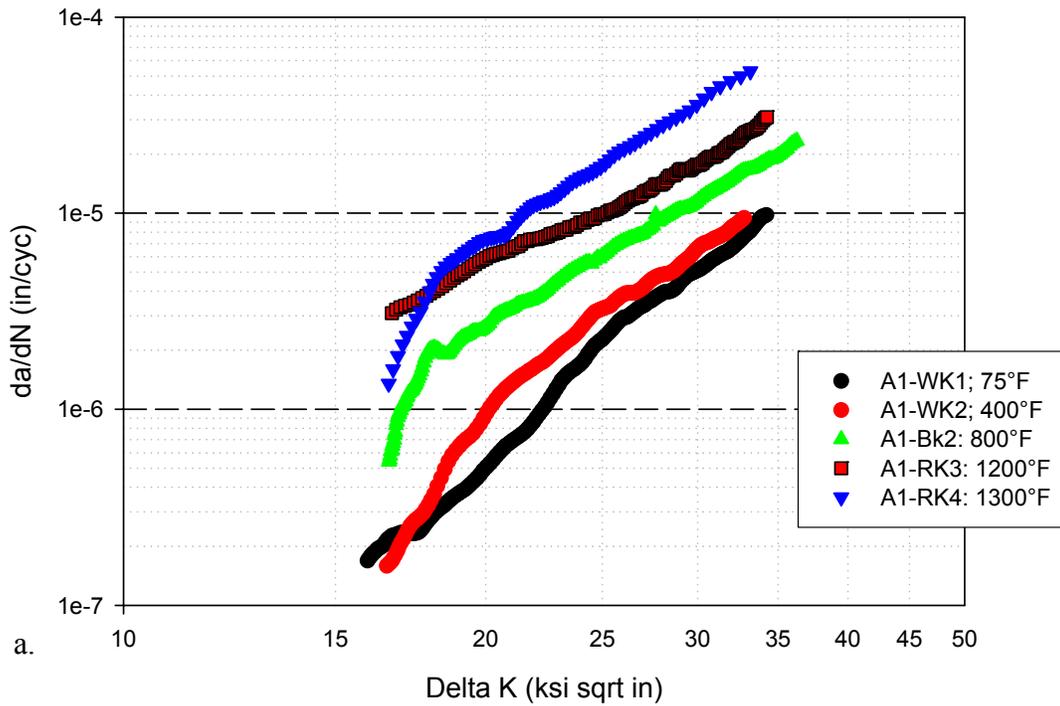


Figure 29.—Failure initiation sites observed for subsolvus notched LCF specimens tested at:  
 a. and b. 800 °F/115 ksi maximum stress, c. and d. 1300 °F/115 ksi, e. and  
 f. 1300 °F/127 ksi with superimposed 90 sec dwell.

LSHR: Supersolvus; Cyclic Crack Growth; R=0.05; 20 cpm



LSHR; Subsolvus; Cyclic Crack Growth: R=0.05; 20 cpm

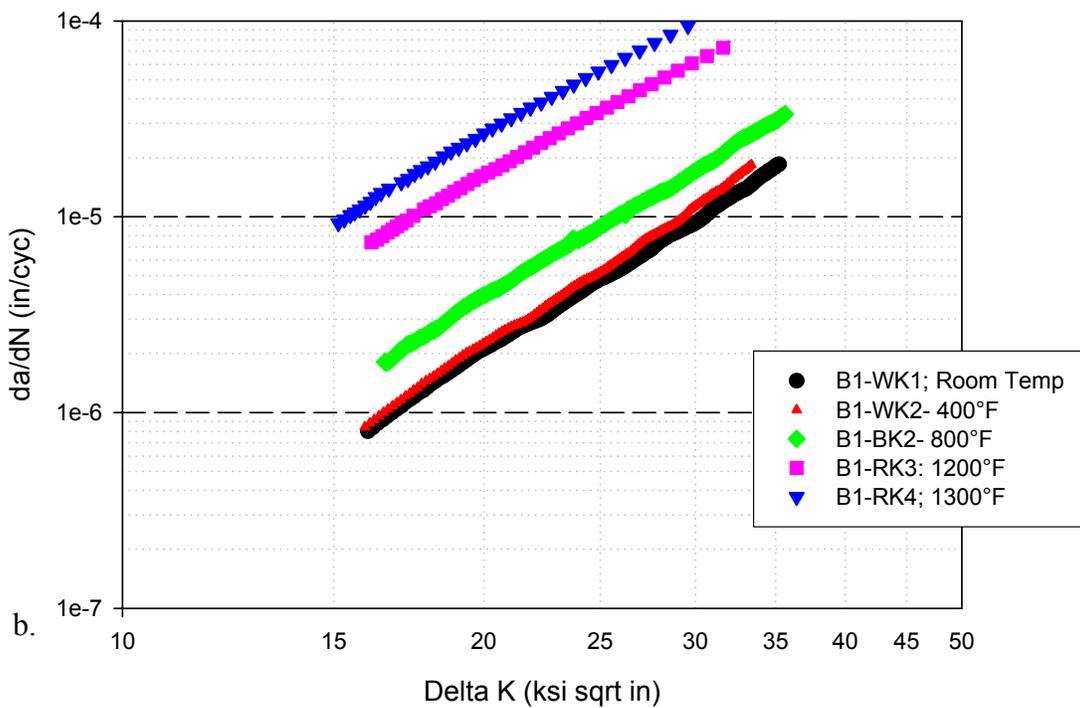
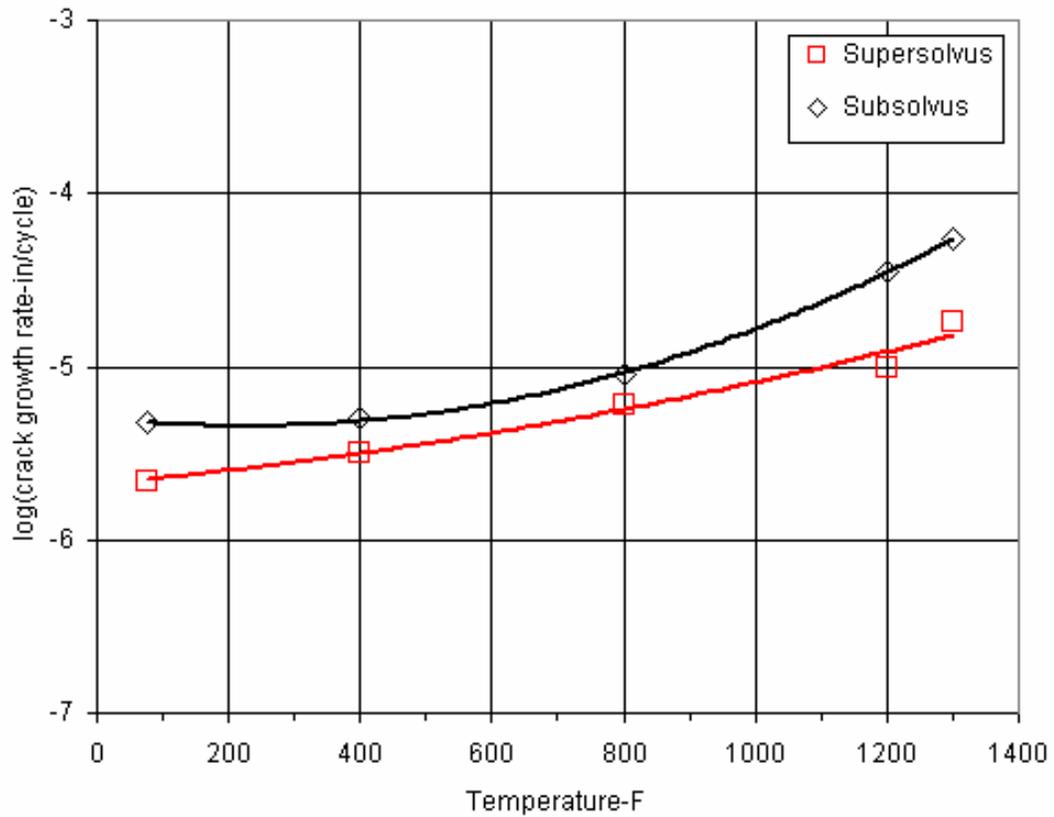


Figure 30.—Comparison of fatigue crack growth rates in cyclic tests at a frequency of 0.33 Hz: a. supersolvus, b. subsolvus.



$$\log(\text{FCGR}) = 2\text{E-}07T^2 + 0.0003420T - 5.6776154$$

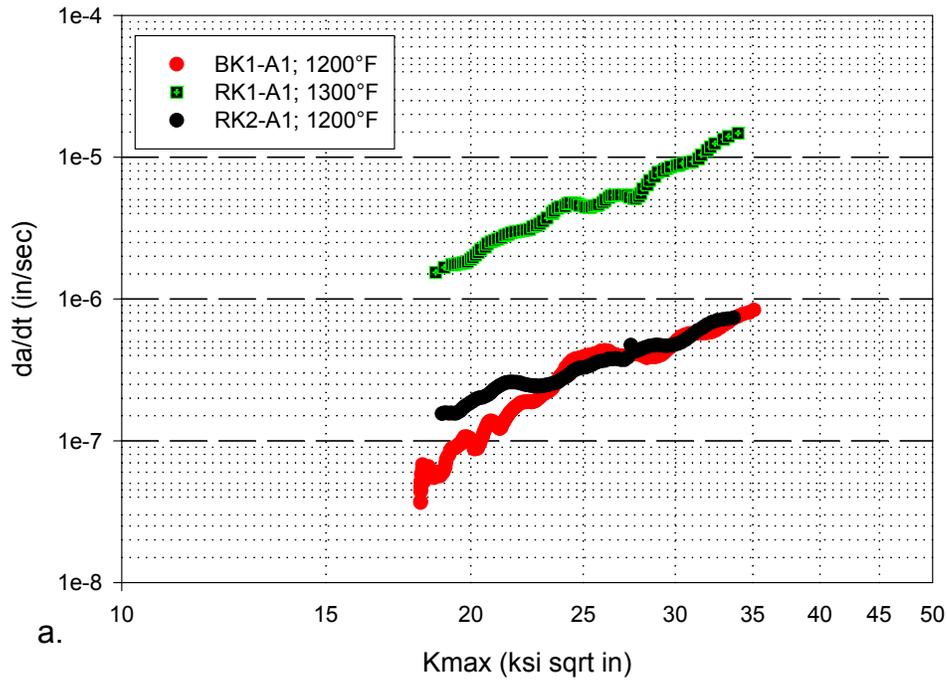
$$R^2 = 0.9718$$

$$\log(\text{FCGR}) = 9\text{E-}07T^2 - 0.0004225T - 5.2957721$$

$$R^2 = 0.9996$$

Figure 31.—Comparison of fatigue crack growth rates in cyclic tests at 25 ksi\*in<sup>0.5</sup> vs. temperature.

LSHR: Supersolvus; 1200°F and 1300°F; 90 sec hold



LSHR; Subsolvus; 1200 and 1300°F; 90 sec hold

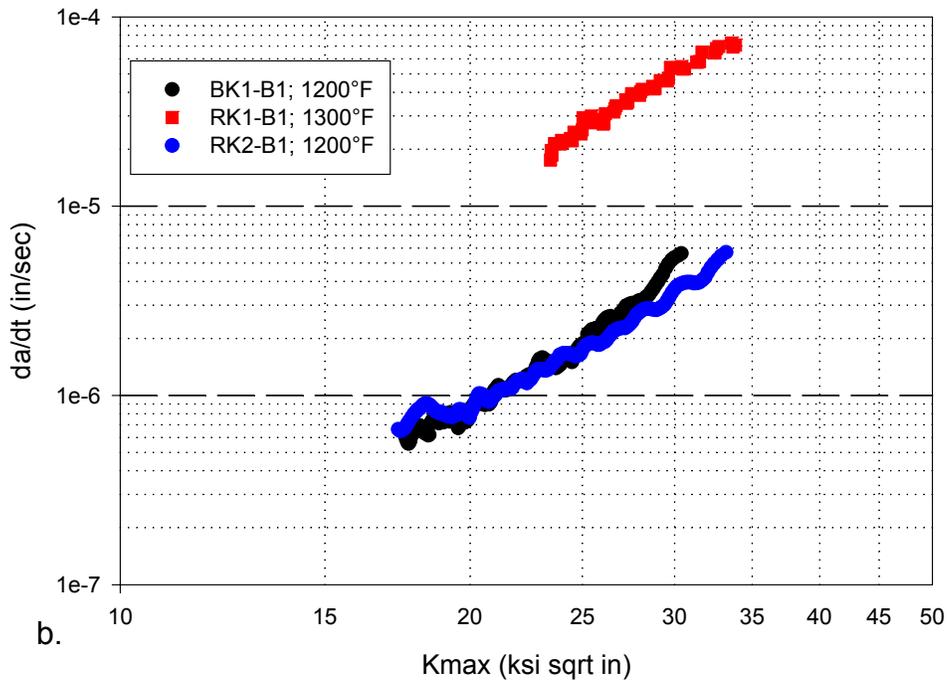


Figure 32.—Comparison of dwell fatigue crack growth rates in tests with 90 s hold at maximum stress: a. supersolvus, b. subsolvus.

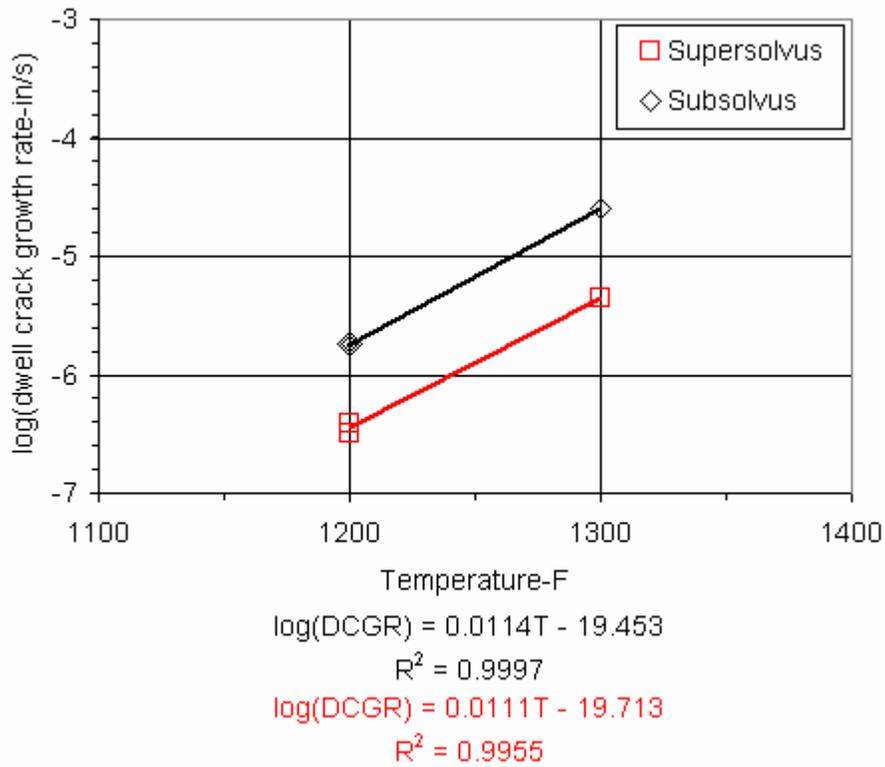


Figure 33.—Comparison of 90 s dwell fatigue crack growth rates at 25 ksi\*in<sup>0.5</sup> vs. temperature.

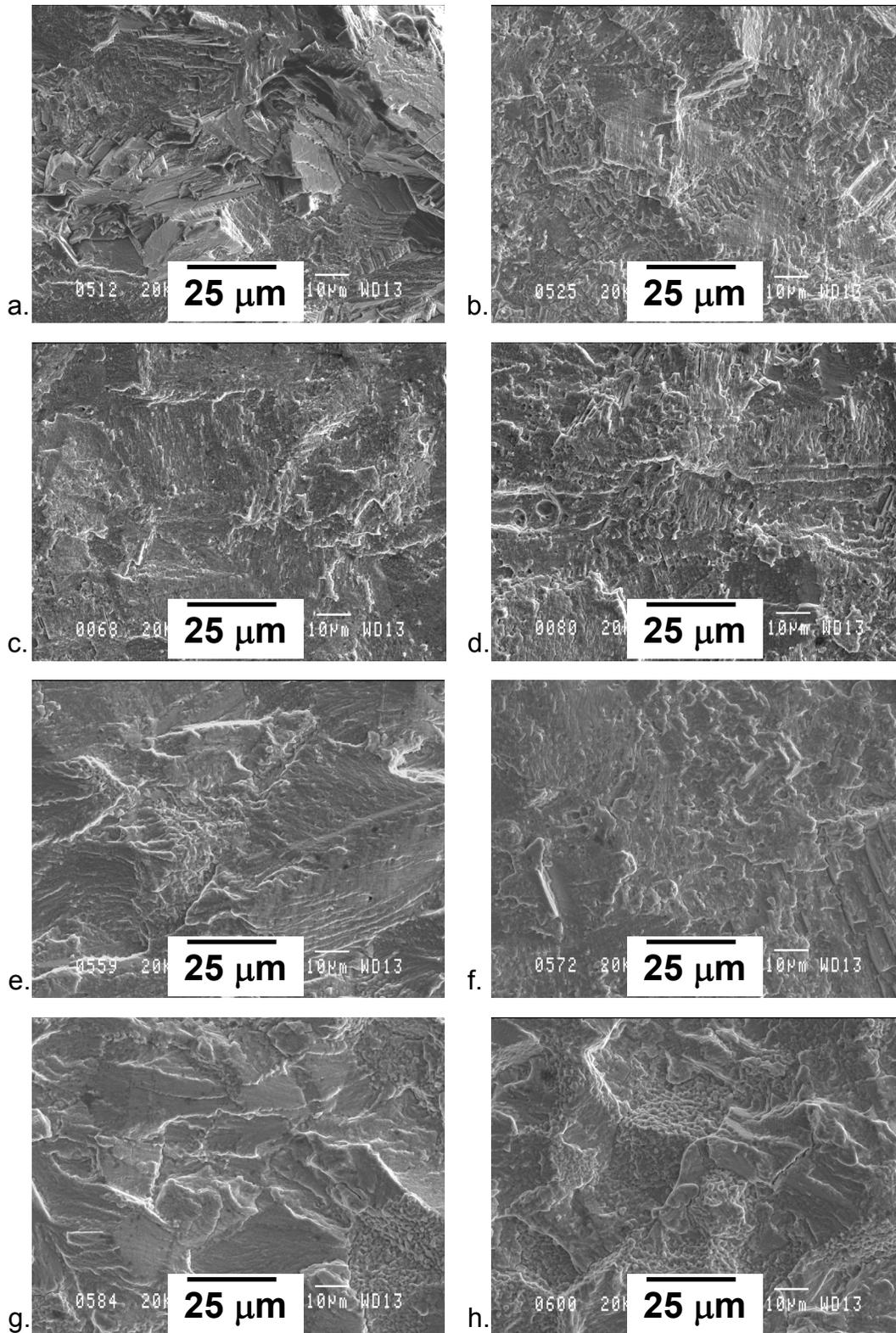


Figure 34.—Fatigue cracking of supersolvus cyclic fatigue crack growth specimens tested at:  
 a. 75 °F, low  $K_{max}$ , b. 75 °F, high  $K_{max}$ , c. 800 °F, low  $K_{max}$ , d. 800 °F, high  $K_{max}$ , e. 1200 °F,  
 low  $K_{max}$ , f. 1200 °F, high  $K_{max}$ , g. 1300 °F, low  $K_{max}$ , h. 1300 °F, high  $K_{max}$

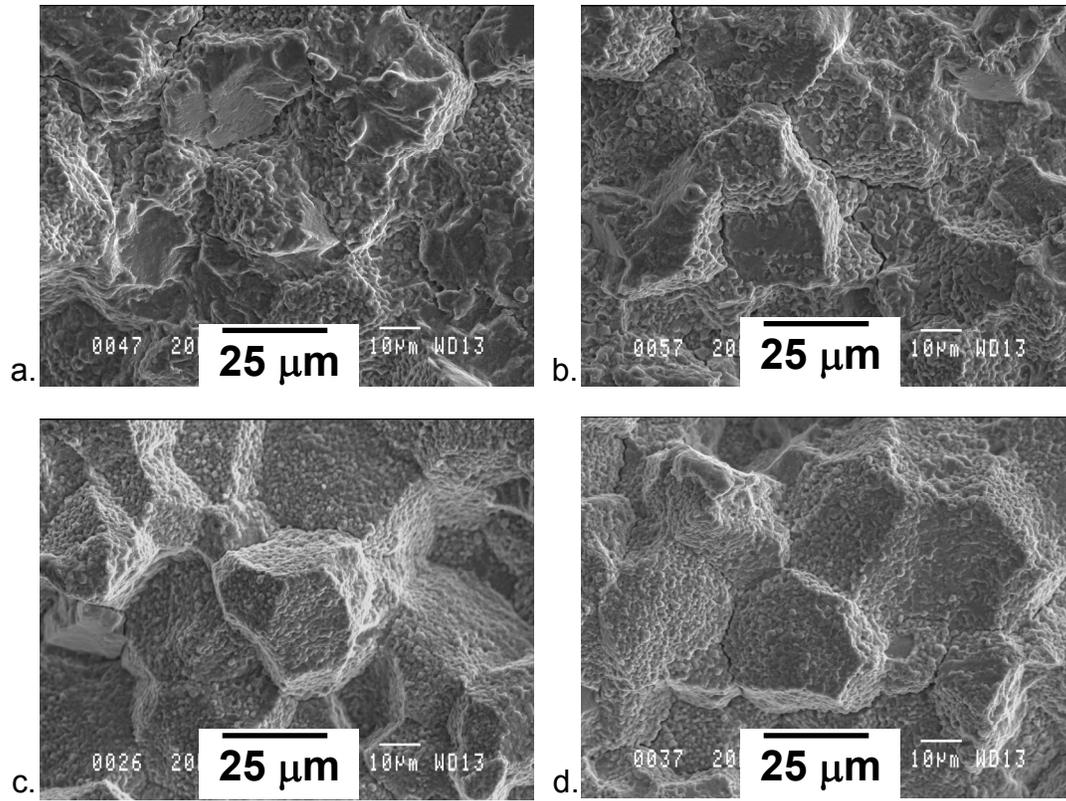


Figure 35.—Fatigue cracking of supersolvus 90 s dwell fatigue crack growth specimens tested at:  
 a. 1200 °F, low  $K_{max}$ , b. 1200 °F, high  $K_{max}$ , c. 1300 °F, low  $K_{max}$ , d. 1300 °F, high  $K_{max}$ .

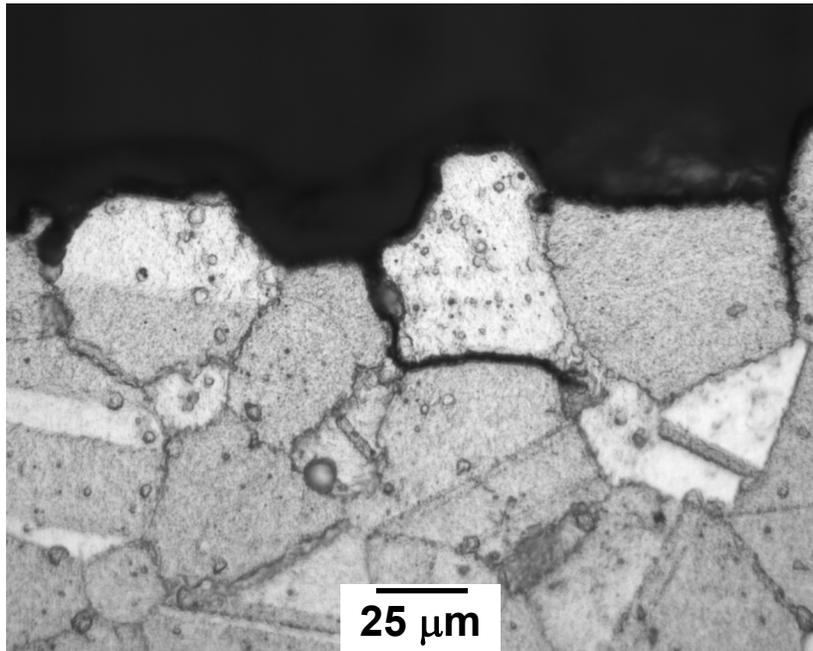


Figure 36.—Metallographic section showing intergranular fatigue cracking of supersolvus specimen tested at 1200 °F in 90 s dwell fatigue crack growth.

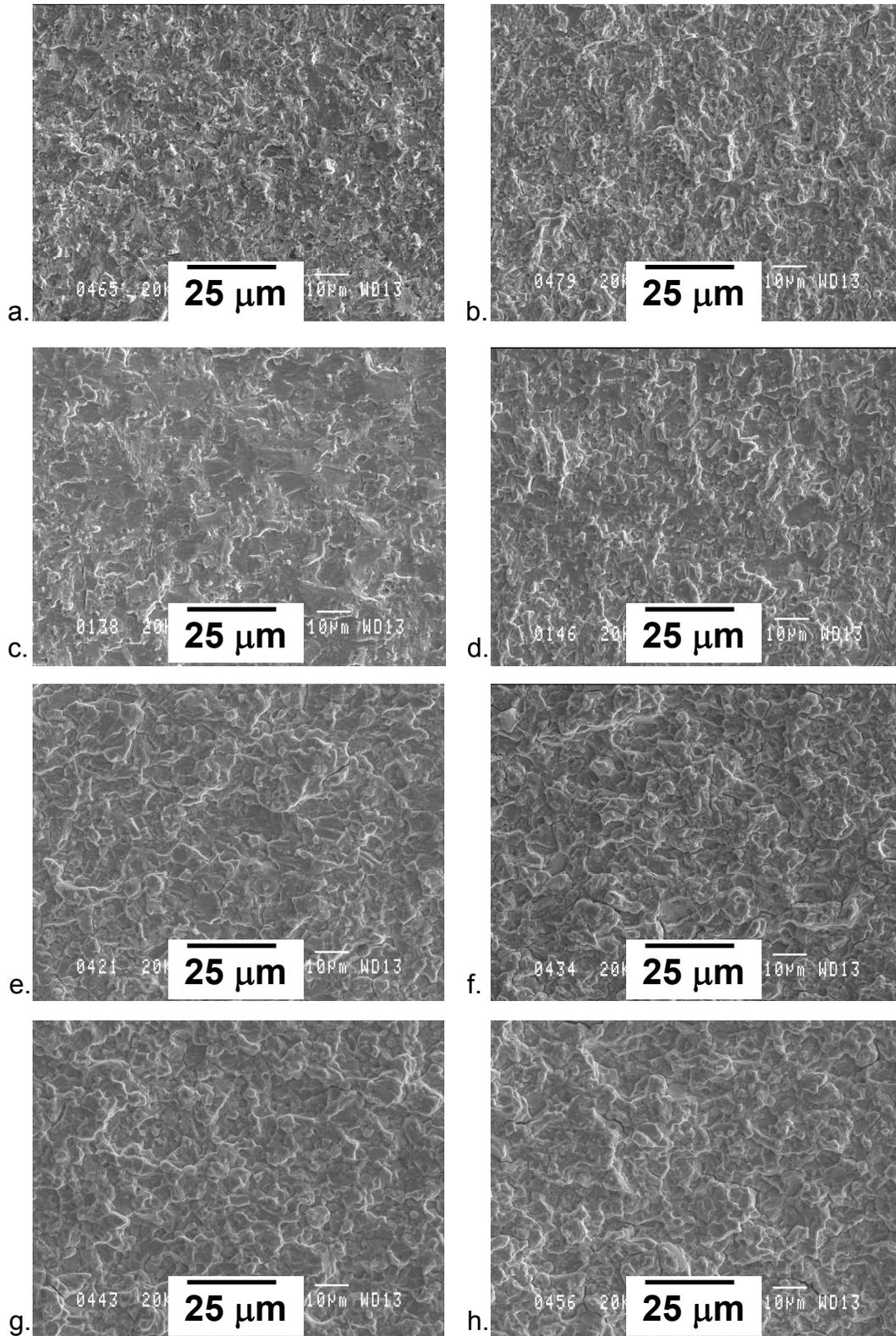


Figure 37.—Fatigue cracking of subsolvus cyclic fatigue crack growth specimens tested at: a. 75 °F, low  $K_{max}$ ; b. 75 °F, high  $K_{max}$ ; c. 800 °F, low  $K_{max}$ ; d. 800 °F, high  $K_{max}$ ; e. 1200 °F, low  $K_{max}$ ; f. 1200 °F, high  $K_{max}$ ; g. 1300 °F, low  $K_{max}$ ; h. 1300 °F, high  $K_{max}$

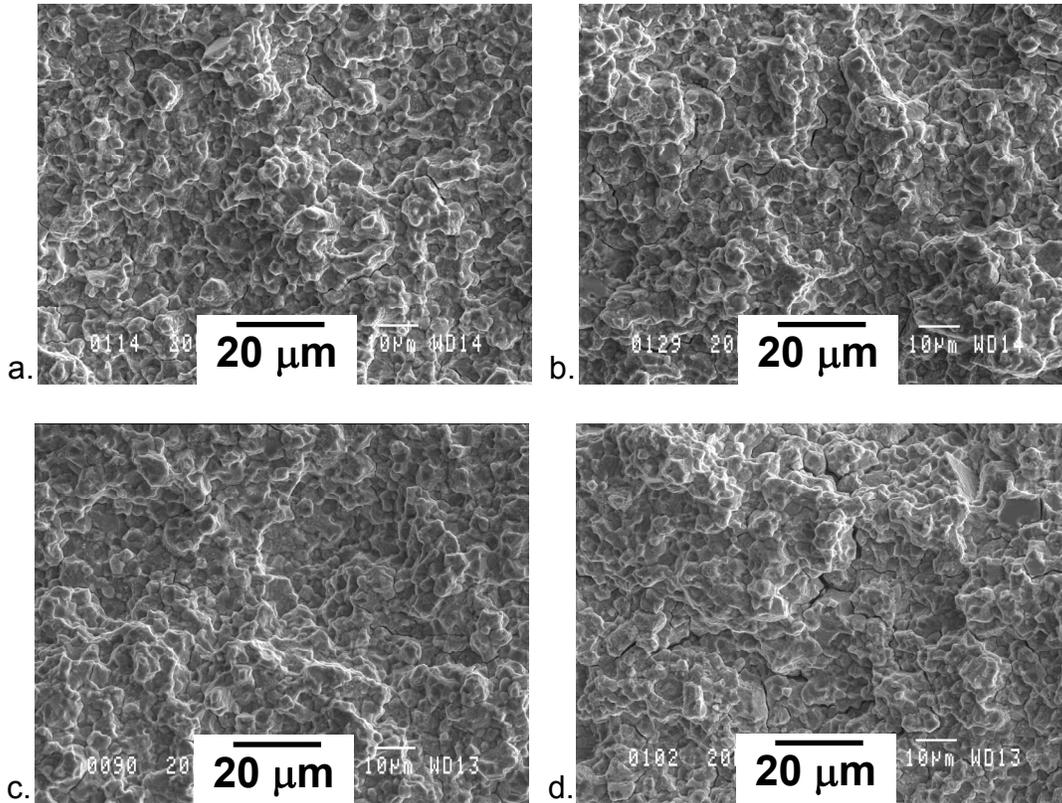


Figure 38.—Fatigue cracking of subsolvus 90 s dwell fatigue crack growth specimens tested at:  
 a. 1200 °F, low  $K_{max}$ , b. 1200 °F, high  $K_{max}$ , c. 1300 °F, low  $K_{max}$ , d. 1300 °F, high  $K_{max}$ .

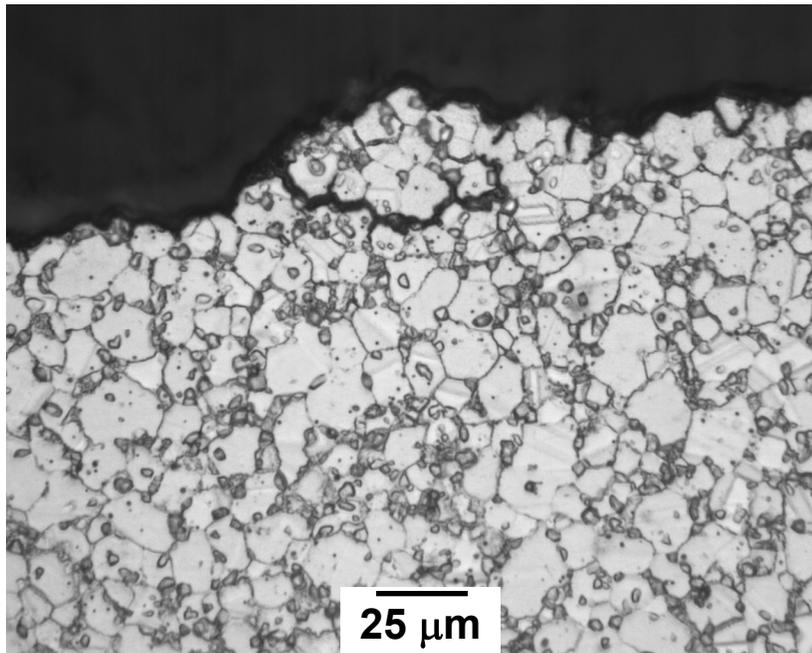


Figure 39.—Metallographic section showing intergranular fatigue cracking of subsolvus specimen tested at 1200 °F in 90 s dwell fatigue crack growth .

## Appendix 1—Tabulated Thermal Diffusivity Results

Temperature- F	Thermal Diffusivity-ft <sup>2</sup> /hr			
SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2
Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus
73	0.10230	0.10269	0.10540	0.10540
122	0.10463	0.10618	0.10811	0.10656
212	0.11005	0.11083	0.11393	0.11276
392	0.12206	0.12129	0.12361	0.12245
572	0.13175	0.13020	0.13330	0.13175
752	0.14183	0.14105	0.14105	0.14028
932	0.15229	0.15190	0.15074	0.14996
1112	0.16236	0.16159	0.16081	0.16236
1292	0.16973	0.17128	0.17050	0.16895
1472	0.18290	0.18329	0.17748	0.17980
1652	0.17980	0.18058	0.17825	0.17631
1832	0.1802	0.18019	0.17670	0.18019
2012	0.1794	0.17980	0.17903	0.17903
2192	0.1848	0.18678	0.18484	0.18368

## Appendix 2—Tabulated Specific Heat Results

Temperature-F	Specific Heat (Heating Data)-BTU/lbF					Temperature-F	Specific Heat (Cooling Data)-BTU/lbF				
	SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2		SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2
	Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus	Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus	
73		0.103	0.103	0.102	0.102	332	0.110	0.107	0.111	0.114	
122		0.104	0.104	0.104	0.104	401	0.110	0.107	0.111	0.114	
167		0.106	0.106	0.106	0.106	410	0.110	0.107	0.111	0.114	
212		0.107	0.108	0.107	0.107	419	0.110	0.108	0.111	0.114	
257		0.108	0.110	0.108	0.108	428	0.111	0.108	0.111	0.114	
302		0.110	0.111	0.109	0.110	437	0.111	0.108	0.112	0.114	
347		0.111	0.112	0.111	0.110	446	0.111	0.108	0.112	0.114	
392		0.112	0.113	0.112	0.111	455	0.111	0.109	0.112	0.115	
437		0.113	0.114	0.113	0.112	464	0.112	0.109	0.112	0.115	
482		0.114	0.114	0.114	0.113	473	0.112	0.109	0.113	0.115	
527		0.114	0.115	0.115	0.113	482	0.112	0.109	0.113	0.115	
572		0.115	0.116	0.116	0.114	491	0.112	0.110	0.113	0.115	
617		0.116	0.116	0.116	0.115	500	0.112	0.110	0.113	0.115	
662		0.116	0.117	0.117	0.115	509	0.113	0.110	0.114	0.115	
707		0.117	0.118	0.118	0.116	518	0.113	0.110	0.114	0.115	
752		0.118	0.118	0.118	0.116	527	0.113	0.110	0.114	0.115	
797		0.118	0.119	0.119	0.117	536	0.113	0.111	0.114	0.116	
842		0.119	0.120	0.119	0.118	545	0.113	0.111	0.115	0.116	
887		0.120	0.121	0.120	0.119	554	0.114	0.111	0.115	0.116	
932		0.120	0.121	0.122	0.119	563	0.114	0.111	0.115	0.116	
941		0.120	0.121	0.122	0.120	572	0.114	0.112	0.116	0.116	
950		0.120	0.121	0.122	0.119	581	0.114	0.112	0.116	0.116	
959		0.120	0.121	0.122	0.119	590	0.115	0.112	0.116	0.117	
968		0.120	0.121	0.121	0.119	599	0.115	0.112	0.116	0.117	
977		0.120	0.121	0.121	0.119	608	0.115	0.113	0.117	0.117	
986		0.121	0.121	0.122	0.120	617	0.115	0.113	0.117	0.117	
995		0.120	0.122	0.121	0.120	626	0.115	0.113	0.117	0.117	
1004		0.120	0.122	0.122	0.120	635	0.115	0.113	0.117	0.117	
1013		0.121	0.122	0.122	0.121	644	0.115	0.113	0.117	0.117	
1022		0.120	0.122	0.122	0.120	653	0.115	0.114	0.117	0.117	
1031		0.120	0.121	0.122	0.120	662	0.115	0.114	0.117	0.117	
1040		0.120	0.121	0.123	0.121	671	0.116	0.114	0.117	0.118	
1049		0.120	0.121	0.123	0.121	680	0.116	0.114	0.117	0.118	
1058		0.120	0.121	0.123	0.122	689	0.116	0.114	0.117	0.118	
1067		0.118	0.120	0.122	0.121	698	0.116	0.115	0.118	0.118	
1076		0.119	0.120	0.123	0.121	707	0.116	0.114	0.118	0.119	
1085		0.118	0.120	0.123	0.122	716	0.116	0.114	0.118	0.118	
1094		0.118	0.120	0.124	0.123	725	0.116	0.114	0.118	0.118	
1103		0.118	0.120	0.123	0.122	734	0.116	0.114	0.118	0.118	
1112		0.118	0.120	0.123	0.123	743	0.116	0.115	0.118	0.118	
1121		0.120	0.122	0.126	0.126	752	0.117	0.115	0.119	0.119	
1130		0.121	0.122	0.127	0.126	761	0.117	0.115	0.119	0.119	
1139		0.121	0.122	0.128	0.126	770	0.117	0.115	0.118	0.119	
1148		0.121	0.124	0.130	0.127	779	0.117	0.115	0.119	0.119	
1157		0.123	0.124	0.130	0.127	788	0.117	0.115	0.119	0.119	
1166		0.125	0.126	0.131	0.129	797	0.118	0.115	0.120	0.119	
1175		0.127	0.128	0.133	0.131	806	0.118	0.116	0.120	0.120	
1184		0.129	0.130	0.135	0.132	815	0.118	0.116	0.120	0.120	
1193		0.132	0.133	0.137	0.133	824	0.118	0.115	0.119	0.119	
1202		0.132	0.133	0.137	0.133	833	0.117	0.115	0.119	0.120	
1211		0.133	0.135	0.138	0.134	842	0.118	0.115	0.120	0.120	
1220		0.135	0.136	0.138	0.134	851	0.118	0.116	0.120	0.120	
1229		0.135	0.136	0.138	0.135	860	0.119	0.116	0.120	0.120	
1238		0.135	0.136	0.138	0.136	869	0.118	0.117	0.120	0.121	
1247		0.136	0.137	0.140	0.137	878	0.118	0.117	0.120	0.120	
1256		0.137	0.138	0.140	0.137	887	0.119	0.117	0.121	0.121	

## Appendix 2—Tabulated Specific Heat Results (cont.)

Temperature- F	Specific Heat (Heating Data)-BTU/lbF				Temperature- F	Specific Heat (Cooling Data)-BTU/lbF			
SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2	SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2
Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus	Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus
1265	0.135	0.136	0.137	0.135	896	0.119	0.117	0.121	0.121
1274	0.136	0.138	0.139	0.136	905	0.119	0.117	0.121	0.121
1283	0.136	0.137	0.139	0.136	914	0.119	0.117	0.121	0.121
1292	0.135	0.137	0.138	0.137	923	0.119	0.117	0.121	0.122
1301	0.138	0.140	0.140	0.139	932	0.120	0.118	0.122	0.122
1310	0.138	0.139	0.139	0.139	941	0.119	0.117	0.121	0.121
1319	0.138	0.140	0.140	0.139	950	0.120	0.118	0.122	0.121
1328	0.138	0.140	0.140	0.139	959	0.120	0.118	0.122	0.122
1337	0.139	0.141	0.142	0.139	968	0.120	0.118	0.122	0.121
1346	0.139	0.142	0.142	0.136	977	0.120	0.118	0.122	0.122
1355	0.140	0.142	0.144	0.138	986	0.120	0.118	0.122	0.123
1364	0.140	0.142	0.142	0.139	995	0.121	0.119	0.122	0.124
1373	0.139	0.140	0.138	0.137	1004	0.121	0.119	0.122	0.123
1382	0.139	0.140	0.140	0.138	1013	0.122	0.120	0.124	0.123
1391	0.141	0.142	0.141	0.139	1022	0.123	0.121	0.125	0.124
1400	0.137	0.141	0.141	0.138	1031	0.123	0.122	0.126	0.124
1409	0.139	0.141	0.142	0.139	1040	0.124	0.123	0.126	0.125
1418	0.143	0.145	0.147	0.142	1049	0.125	0.123	0.126	0.126
1427	0.142	0.144	0.149	0.141	1058	0.125	0.123	0.126	0.126
1436	0.142	0.145	0.148	0.143	1067	0.125	0.122	0.127	0.126
1445	0.140	0.144	0.146	0.142	1076	0.124	0.123	0.127	0.127
1454	0.144	0.146	0.148	0.143	1085	0.125	0.123	0.127	0.128
1463	0.144	0.149	0.151	0.146	1094	0.125	0.123	0.126	0.127
1472	0.147	0.149	0.154	0.149	1103	0.126	0.124	0.128	0.128
1481	0.144	0.147	0.152	0.147	1112	0.128	0.125	0.129	0.130
1490	0.145	0.148	0.152	0.149	1121	0.129	0.126	0.131	0.131
1499	0.147	0.149	0.154	0.152	1130	0.129	0.128	0.132	0.131
1508	0.148	0.153	0.157	0.156	1139	0.130	0.130	0.134	0.134
1517	0.154	0.157	0.165	0.159	1148	0.131	0.130	0.134	0.135
1526	0.153	0.158	0.165	0.160	1157	0.133	0.131	0.135	0.135
1535	0.160	0.165	0.172	0.168	1166	0.133	0.130	0.135	0.134
1544	0.157	0.162	0.171	0.167	1175	0.134	0.133	0.136	0.136
1553	0.163	0.166	0.174	0.171	1184	0.136	0.134	0.137	0.138
1562	0.163	0.169	0.177	0.173	1193	0.134	0.133	0.136	0.136
1571	0.166	0.171	0.177	0.173	1202	0.135	0.132	0.136	0.136
1580	0.176	0.179	0.182	0.176	1211	0.136	0.134	0.138	0.138
1589	0.176	0.180	0.184	0.177	1220	0.137	0.134	0.139	0.139
1598	0.177	0.182	0.185	0.183	1229	0.137	0.135	0.139	0.140
1607	0.182	0.185	0.192	0.189	1238	0.138	0.137	0.139	0.139
1616	0.185	0.191	0.190	0.188	1247	0.140	0.136	0.140	0.140
1625	0.185	0.187	0.191	0.190	1256	0.140	0.138	0.142	0.142
1634	0.192	0.194	0.192	0.188	1265	0.139	0.137	0.142	0.140
1643	0.192	0.190	0.194	0.192	1274	0.141	0.138	0.144	0.143
1652	0.196	0.198	0.194	0.193	1283	0.141	0.139	0.145	0.144
1661	0.192	0.194	0.191	0.189	1292	0.143	0.142	0.144	0.145
1670	0.201	0.199	0.199	0.196	1301	0.142	0.139	0.143	0.144
1679	0.197	0.198	0.197	0.194	1310	0.142	0.139	0.142	0.145
1688	0.197	0.203	0.200	0.196	1319	0.143	0.141	0.145	0.145
1697	0.196	0.202	0.198	0.196	1328	0.145	0.143	0.148	0.148
1706	0.203	0.204	0.206	0.203	1337	0.146	0.143	0.149	0.148
1715	0.201	0.206	0.210	0.205	1346	0.148	0.146	0.150	0.153
1724	0.204	0.203	0.201	0.200	1355	0.145	0.144	0.149	0.148
1733	0.209	0.209	0.208	0.202	1364	0.150	0.149	0.151	0.153
1742	0.204	0.199	0.203	0.193	1373	0.148	0.146	0.148	0.152
1751	0.212	0.206	0.207	0.203	1382	0.151	0.149	0.153	0.154
1760	0.210	0.207	0.210	0.207	1391	0.149	0.149	0.150	0.154

## Appendix 2—Tabulated Specific Heat Results (cont.)

Temperature-F					Temperature-F				
SpecID	Specific Heat (Heating Data)-BTU/lbF				SpecID	Specific Heat (Cooling Data)-BTU/lbF			
	2-L2-1	2-L2-2	T7-1-1	T7-1-2		2-L2-1	2-L2-2	T7-1-1	T7-1-2
Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus	Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus
1769	0.206	0.203	0.203	0.202	1400	0.149	0.148	0.153	0.153
1778	0.213	0.207	0.210	0.210	1409	0.151	0.151	0.154	0.156
1787	0.209	0.213	0.215	0.208	1418	0.150	0.149	0.156	0.152
1796	0.210	0.217	0.213	0.210	1427	0.159	0.154	0.162	0.160
1805	0.208	0.208	0.213	0.208	1436	0.149	0.151	0.155	0.154
1814	0.224	0.220	0.219	0.220	1445	0.157	0.155	0.155	0.161
1823	0.217	0.211	0.219	0.213	1454	0.156	0.153	0.157	0.160
1832	0.218	0.216	0.227	0.217	1463	0.157	0.156	0.160	0.158
1841	0.215	0.215	0.225	0.219	1472	0.156	0.157	0.163	0.160
1850	0.225	0.224	0.228	0.226	1481	0.156	0.155	0.160	0.160
1859	0.229	0.222	0.229	0.225	1490	0.161	0.159	0.162	0.162
1868	0.223	0.223	0.222	0.220	1499	0.163	0.161	0.163	0.164
1877	0.230	0.224	0.228	0.227	1508	0.164	0.164	0.166	0.167
1886	0.229	0.226	0.230	0.231	1517	0.156	0.156	0.157	0.162
1895	0.235	0.237	0.239	0.232	1526	0.162	0.159	0.164	0.166
1904	0.230	0.234	0.233	0.226	1535	0.163	0.159	0.161	0.163
1913	0.235	0.235	0.232	0.232	1544	0.168	0.162	0.167	0.169
1922	0.239	0.239	0.245	0.238	1553	0.168	0.161	0.171	0.170
1931	0.245	0.245	0.248	0.242	1562	0.169	0.167	0.172	0.172
1940	0.256	0.251	0.255	0.250	1571	0.166	0.164	0.166	0.170
1949	0.251	0.250	0.253	0.257	1580	0.162	0.160	0.163	0.167
1958	0.245	0.250	0.243	0.252	1589	0.163	0.168	0.172	0.170
1967	0.264	0.258	0.267	0.255	1598	0.167	0.169	0.168	0.171
1976	0.259	0.265	0.259	0.253	1607	0.167	0.167	0.168	0.172
1985	0.264	0.263	0.261	0.249	1616	0.169	0.171	0.177	0.177
1994	0.268	0.270	0.275	0.257	1625	0.169	0.169	0.170	0.172
2003	0.272	0.275	0.275	0.266	1634	0.170	0.168	0.172	0.174
2012	0.265	0.279	0.273	0.275	1643	0.173	0.171	0.175	0.177
2021	0.264	0.271	0.272	0.266	1652	0.171	0.169	0.172	0.172
2030	0.279	0.276	0.283	0.275	1661	0.177	0.177	0.178	0.177
2039	0.287	0.287	0.287	0.285	1670	0.171	0.175	0.174	0.177
2048	0.289	0.290	0.289	0.284	1679	0.178	0.180	0.185	0.185
2057	0.297	0.294	0.292	0.274	1688	0.176	0.178	0.183	0.182
2066	0.292	0.285	0.270	0.252	1697	0.183	0.179	0.182	0.180
2075	0.302	0.297	0.253	0.246	1706	0.184	0.184	0.188	0.187
2084	0.310	0.316	0.248	0.256	1715	0.184	0.186	0.189	0.186
2093	0.291	0.292	0.233	0.238	1724	0.180	0.181	0.184	0.183
2102	0.293	0.292	0.262	0.250	1733	0.184	0.186	0.186	0.189
2111	0.231	0.227	0.271	0.258	1742	0.194	0.191	0.201	0.197
2120	0.196	0.204	0.263	0.260	1751	0.192	0.187	0.192	0.188
2129	0.183	0.192	0.256	0.249	1760	0.198	0.197	0.199	0.201
2138	0.183	0.178	0.235	0.233	1769	0.192	0.195	0.199	0.199
2147	0.172	0.170	0.209	0.210	1778	0.198	0.196	0.199	0.202
2156	0.174	0.176	0.207	0.201	1787	0.201	0.199	0.198	0.202
2165	0.178	0.189	0.207	0.204	1796	0.201	0.198	0.205	0.208
2174	0.178	0.182	0.198	0.186	1805	0.205	0.206	0.202	0.209
2183	0.220	0.221	0.237	0.229	1814	0.204	0.204	0.207	0.207
2192	0.252	0.251	0.260	0.260	1823	0.205	0.203	0.212	0.216
					1832	0.206	0.203	0.206	0.211
					1841	0.218	0.216	0.220	0.222
					1850	0.209	0.213	0.211	0.220
					1859	0.213	0.213	0.219	0.218
					1868	0.221	0.218	0.224	0.225
					1877	0.219	0.220	0.223	0.226
					1886	0.231	0.233	0.234	0.239
					1895	0.224	0.224	0.232	0.227

## Appendix 2—Tabulated Specific Heat Results (cont.)

Temperature- F	Specific Heat (Cooling Data)-BTU/lbF			
	2-L2-1	2-L2-2	T7-1-1	T7-1-2
SpecID	Supersolvus	Supersolvus	Subsolvus	Subsolvus
1904	0.229	0.232	0.238	0.232
1913	0.227	0.225	0.224	0.233
1922	0.239	0.236	0.236	0.246
1931	0.251	0.250	0.257	0.260
1940	0.239	0.239	0.239	0.241
1949	0.253	0.251	0.247	0.252
1958	0.274	0.269	0.272	0.272
1967	0.261	0.262	0.268	0.262
1976	0.267	0.273	0.273	0.273
1985	0.283	0.292	0.297	0.300
1994	0.308	0.309	0.313	0.322
2003	0.322	0.327	0.333	0.333
2012	0.376	0.373	0.389	0.394
2021	0.388	0.392	0.397	0.399
2030	0.321	0.315	0.325	0.334
2039	0.176	0.174	0.187	0.188
2048	0.168	0.163	0.169	0.174
2057	0.169	0.164	0.168	0.176
2066	0.171	0.167	0.172	0.176
2075	0.175	0.177	0.167	0.178
2084	0.166	0.168	0.173	0.176
2093	0.173	0.171	0.169	0.179
2102	0.175	0.175	0.181	0.178
2111	0.179	0.170	0.181	0.179
2120	0.179	0.182	0.177	0.181
2129	0.175	0.174	0.174	0.175
2138	0.174	0.173	0.173	0.178
2147	0.189	0.176	0.186	0.198
2156	0.177	0.178	0.186	0.195
2165	0.189	0.184	0.185	0.188
2174	0.188	0.188	0.192	0.198
2183	0.195	0.196	0.203	0.200
2192	0.190	0.178	0.189	0.194

### Appendix 3—Tabulated Thermal Conductivity Results

Temperature- F	Thermal Conductivity-BTU/(hr ft F)			
SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2
Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus
73	5.455	5.425	5.558	5.578
122	5.683	5.713	5.825	5.755
212	6.132	6.146	6.321	6.259
392	7.138	7.039	7.179	7.070
572	7.896	7.764	7.983	7.812
752	8.692	8.614	8.644	8.463
932	9.508	9.473	9.488	9.257
1112	10.559	10.410	10.414	10.519
1292	11.550	11.546	11.562	11.471
1472	13.246	13.064	12.734	12.907
1652	13.676	13.587	13.482	13.342
1832	14.437	14.348	14.097	14.382
2012	15.187	14.965	14.987	15.032
2192	16.396	16.480	16.374	16.279

## Appendix 4—Tabulated Thermal Expansion Results

Temperature F	Thermal Expansion (Heating Data)-in/in				Temperature F	Thermal Expansion (Cooling Data)-in/in			
SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2	SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2
Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus	Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus
68	0.00000	0.00000	0.00000	0.00000	2192	0.02245	0.02210	0.02192	0.02209
86	0.00013	0.00012	0.00012	0.00012	2174	0.02221	0.02180	0.02167	0.02182
104	0.00025	0.00025	0.00025	0.00024	2156	0.02195	0.02150	0.02140	0.02155
122	0.00037	0.00037	0.00037	0.00037	2138	0.02170	0.02124	0.02115	0.02130
140	0.00050	0.00050	0.00049	0.00049	2120	0.02146	0.02100	0.02092	0.02106
158	0.00062	0.00062	0.00061	0.00061	2102	0.02123	0.02076	0.02069	0.02083
176	0.00074	0.00074	0.00073	0.00073	2084	0.02098	0.02051	0.02045	0.02058
194	0.00087	0.00086	0.00086	0.00086	2066	0.02068	0.02021	0.02016	0.02028
212	0.00099	0.00099	0.00099	0.00098	2048	0.02032	0.01986	0.01981	0.01992
230	0.00112	0.00112	0.00111	0.00111	2030	0.01991	0.01947	0.01942	0.01953
248	0.00124	0.00124	0.00124	0.00123	2012	0.01945	0.01904	0.01897	0.01907
266	0.00137	0.00137	0.00137	0.00136	1994	0.01897	0.01856	0.01850	0.01858
284	0.00150	0.00150	0.00149	0.00149	1976	0.01857	0.01813	0.01808	0.01816
302	0.00163	0.00163	0.00162	0.00162	1958	0.01819	0.01775	0.01771	0.01778
320	0.00176	0.00176	0.00175	0.00175	1940	0.01783	0.01738	0.01735	0.01742
338	0.00189	0.00189	0.00188	0.00187	1922	0.01747	0.01703	0.01701	0.01707
356	0.00202	0.00202	0.00201	0.00200	1904	0.01713	0.01669	0.01667	0.01673
374	0.00215	0.00215	0.00214	0.00214	1886	0.01680	0.01636	0.01634	0.01640
392	0.00228	0.00228	0.00228	0.00227	1868	0.01648	0.01604	0.01602	0.01607
410	0.00241	0.00241	0.00241	0.00240	1850	0.01617	0.01573	0.01571	0.01576
428	0.00254	0.00254	0.00254	0.00253	1832	0.01586	0.01543	0.01541	0.01546
446	0.00268	0.00268	0.00267	0.00266	1814	0.01557	0.01514	0.01511	0.01516
464	0.00281	0.00281	0.00281	0.00280	1796	0.01528	0.01485	0.01483	0.01488
482	0.00295	0.00295	0.00294	0.00293	1778	0.01500	0.01457	0.01455	0.01460
500	0.00308	0.00308	0.00308	0.00307	1760	0.01473	0.01430	0.01427	0.01433
518	0.00321	0.00322	0.00321	0.00320	1742	0.01447	0.01403	0.01401	0.01406
536	0.00335	0.00335	0.00335	0.00334	1724	0.01421	0.01377	0.01375	0.01380
554	0.00349	0.00349	0.00348	0.00348	1706	0.01395	0.01352	0.01349	0.01355
572	0.00362	0.00363	0.00362	0.00361	1688	0.01370	0.01328	0.01325	0.01330
590	0.00376	0.00377	0.00376	0.00375	1670	0.01346	0.01304	0.01301	0.01306
608	0.00389	0.00390	0.00390	0.00389	1652	0.01323	0.01280	0.01277	0.01283
626	0.00403	0.00404	0.00404	0.00403	1634	0.01300	0.01257	0.01254	0.01260
644	0.00417	0.00418	0.00418	0.00417	1616	0.01277	0.01235	0.01232	0.01238
662	0.00431	0.00432	0.00432	0.00431	1598	0.01255	0.01213	0.01210	0.01216
680	0.00446	0.00446	0.00446	0.00445	1580	0.01233	0.01191	0.01188	0.01194
698	0.00460	0.00460	0.00460	0.00459	1562	0.01211	0.01170	0.01167	0.01173
716	0.00474	0.00474	0.00474	0.00473	1544	0.01190	0.01149	0.01146	0.01152
734	0.00488	0.00489	0.00488	0.00487	1526	0.01169	0.01128	0.01125	0.01131
752	0.00502	0.00503	0.00503	0.00502	1508	0.01148	0.01108	0.01105	0.01111
770	0.00517	0.00517	0.00517	0.00516	1490	0.01128	0.01088	0.01085	0.01091
788	0.00531	0.00532	0.00531	0.00530	1472	0.01107	0.01068	0.01065	0.01071
806	0.00545	0.00546	0.00546	0.00545	1454	0.01087	0.01048	0.01045	0.01052
824	0.00560	0.00561	0.00560	0.00559	1436	0.01067	0.01028	0.01026	0.01033
842	0.00574	0.00575	0.00575	0.00574	1418	0.01049	0.01009	0.01007	0.01014
860	0.00589	0.00590	0.00589	0.00589	1400	0.01029	0.00990	0.00988	0.00996
878	0.00603	0.00604	0.00604	0.00603	1382	0.01010	0.00971	0.00969	0.00977
896	0.00618	0.00619	0.00619	0.00617	1364	0.00991	0.00952	0.00951	0.00959
914	0.00633	0.00633	0.00633	0.00632	1346	0.00973	0.00933	0.00933	0.00941
932	0.00647	0.00648	0.00648	0.00646	1328	0.00955	0.00915	0.00915	0.00924
950	0.00662	0.00662	0.00662	0.00661	1310	0.00937	0.00897	0.00897	0.00906
968	0.00676	0.00676	0.00676	0.00675	1292	0.00919	0.00879	0.00880	0.00889
986	0.00690	0.00691	0.00691	0.00690	1274	0.00901	0.00861	0.00862	0.00871
1004	0.00705	0.00705	0.00705	0.00704	1256	0.00883	0.00843	0.00844	0.00854
1022	0.00719	0.00720	0.00720	0.00719	1238	0.00866	0.00825	0.00827	0.00837
1040	0.00734	0.00734	0.00735	0.00734	1220	0.00848	0.00808	0.00810	0.00820
1058	0.00750	0.00750	0.00751	0.00749	1202	0.00831	0.00790	0.00792	0.00803

## Appendix 4—Tabulated Thermal Expansion Results (cont.)

Temperature: F	Thermal Expansion (Heating Data)-in/in				Temperature: F	Thermal Expansion (Cooling Data)-in/in			
SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2	SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2
Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus	Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus
1076	0.00765	0.00765	0.00767	0.00765	1184	0.00813	0.00773	0.00775	0.00786
1094	0.00782	0.00781	0.00783	0.00781	1166	0.00796	0.00755	0.00758	0.00769
1112	0.00798	0.00798	0.00799	0.00797	1148	0.00779	0.00739	0.00741	0.00753
1130	0.00815	0.00814	0.00816	0.00814	1130	0.00763	0.00722	0.00725	0.00736
1148	0.00832	0.00831	0.00832	0.00830	1112	0.00746	0.00705	0.00708	0.00720
1166	0.00848	0.00848	0.00849	0.00846	1094	0.00729	0.00688	0.00692	0.00703
1184	0.00866	0.00865	0.00865	0.00863	1076	0.00713	0.00672	0.00675	0.00687
1202	0.00883	0.00882	0.00882	0.00879	1058	0.00707	0.00656	0.00659	0.00671
1220	0.00900	0.00899	0.00899	0.00896	1040	0.00691	0.00640	0.00643	0.00656
1238	0.00917	0.00916	0.00915	0.00912	1022	0.00676	0.00626	0.00627	0.00642
1256	0.00934	0.00933	0.00931	0.00929	1004	0.00661	0.00613	0.00612	0.00627
1274	0.00951	0.00949	0.00948	0.00945	986	0.00646	0.00599	0.00596	0.00612
1292	0.00968	0.00966	0.00964	0.00961	968	0.00632	0.00585	0.00583	0.00597
1310	0.00985	0.00982	0.00980	0.00978	950	0.00617	0.00571	0.00568	0.00582
1328	0.01002	0.00999	0.00996	0.00995	932	0.00603	0.00558	0.00555	0.00567
1346	0.01019	0.01016	0.01013	0.01012	914	0.00589	0.00545	0.00541	0.00555
1364	0.01037	0.01033	0.01031	0.01030	896	0.00575	0.00532		0.00540
1382	0.01055	0.01051	0.01049	0.01049	878	0.00561	0.00519		0.00525
1400	0.01073	0.01069	0.01068	0.01069	860	0.00547	0.00505		0.00511
1418	0.01092	0.01087	0.01088	0.01090	842	0.00533	0.00492		0.00500
1436	0.01111	0.01107	0.01109	0.01111	824	0.00519	0.00478		0.00487
1454	0.01132	0.01127	0.01130	0.01134	806	0.00505	0.00464		0.00473
1472	0.01153	0.01148	0.01152	0.01158	788	0.00492	0.00452		0.00461
1490	0.01174	0.01170	0.01174	0.01182	770	0.00479	0.00438		0.00448
1508	0.01197	0.01192	0.01197	0.01206	752	0.00466	0.00425		0.00436
1526	0.01219	0.01214	0.01221	0.01231	734	0.00453	0.00412		0.00423
1544	0.01242	0.01237	0.01245	0.01257	716	0.00439	0.00398		0.00411
1562	0.01266	0.01261	0.01269	0.01282	698	0.00427	0.00385		0.00399
1580	0.01290	0.01285	0.01294	0.01308	680	0.00414	0.00372		0.00386
1598	0.01314	0.01309	0.01319	0.01334	662	0.00403	0.00359		0.00373
1616	0.01339	0.01334	0.01344	0.01360	644	0.00390	0.00346		0.00362
1634	0.01364	0.01359	0.01369	0.01386	626	0.00377	0.00332		0.00350
1652	0.01389	0.01384	0.01395	0.01412	608	0.00364	0.00319		0.00338
1670	0.01415	0.01409	0.01422	0.01439	590	0.00351	0.00305		0.00326
1688	0.01440	0.01435	0.01449	0.01466	572	0.00338	0.00292		0.00313
1706	0.01467	0.01462	0.01476	0.01493	554	0.00325	0.00279		0.00301
1724	0.01494	0.01489	0.01504	0.01521	536	0.00312	0.00266		0.00289
1742	0.01521	0.01517	0.01533	0.01549	518	0.00300	0.00253		0.00278
1760	0.01549	0.01544	0.01561	0.01577	500	0.00287	0.00240		0.00265
1778	0.01578	0.01573	0.01590	0.01605	482	0.00275	0.00227		0.00253
1796	0.01607	0.01602	0.01619	0.01634	464	0.00263	0.00215		0.00241
1814	0.01637	0.01632	0.01648	0.01662	446	0.00250	0.00202		0.00229
1832	0.01667	0.01662	0.01677	0.01691	428	0.00238	0.00189		0.00217
1850	0.01698	0.01693	0.01707	0.01721	410	0.00226	0.00176		0.00207
1868	0.01730	0.01725	0.01737	0.01751	392	0.00214	0.00163		0.00202
1886	0.01762	0.01757	0.01768	0.01782	72	-0.00020	-0.00055	-0.00015	-0.00022
1904	0.01795	0.01789	0.01800	0.01814					
1922	0.01830	0.01823	0.01832	0.01846					
1940	0.01864	0.01857	0.01864	0.01879					
1958	0.01900	0.01892	0.01896	0.01912					
1976	0.01937	0.01928	0.01929	0.01946					
1994	0.01975	0.01965	0.01962	0.01980					
2012	0.02013	0.02003	0.01993	0.02013					
2030	0.02053	0.02042	0.02023	0.02043					
2048	0.02093	0.02081	0.02050	0.02068					

## Appendix 4—Tabulated Thermal Expansion Results (cont.)

Temperature F	Thermal Expansion (Heating Data)-in/in			
SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2
Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus
2066	0.02129	0.02115	0.02077	0.02094
2084	0.02161	0.02145	0.02102	0.02119
2102	0.02188	0.02172	0.02124	0.02140
2120	0.02211	0.02193	0.02143	0.02159
2138	0.02227	0.02208	0.02159	0.02177
2156	0.02241	0.02218	0.02176	0.02193
2174	0.02252	0.02225	0.02190	0.02206
2192	0.02260	0.02230	0.02202	0.02217

## Appendix 5—Tabulated Instantaneous CTE Results

Temperature F	Instantaneous CTE- $\mu$ in/inF				
	SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2
	Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus
212		6.98726	7.03407	6.95703	6.94125
230		6.96631	6.95631	6.97119	7.01381
248		7.03745	7.00040	7.07160	6.98049
266		7.09225	7.11513	7.12332	7.07372
284		7.16539	7.17022	7.14482	7.15031
302		7.17642	7.19646	7.19831	7.24454
320		7.15570	7.15863	7.15843	7.13385
338		7.15034	7.13390	7.14249	7.11194
356		7.29233	7.30506	7.28662	7.31976
374		7.29257	7.38488	7.36074	7.40441
392		7.30056	7.32376	7.33042	7.27966
410		7.42643	7.33586	7.33594	7.27768
428		7.31055	7.34466	7.34379	7.33410
446		7.39844	7.42278	7.44467	7.40823
464		7.49748	7.46263	7.43382	7.49371
482		7.44904	7.48688	7.48125	7.47477
500		7.48294	7.52290	7.48005	7.49062
518		7.49366	7.49433	7.51715	7.51941
536		7.52453	7.60425	7.58845	7.59291
554		7.56871	7.69358	7.66128	7.64905
572		7.57020	7.66833	7.66255	7.65485
590		7.56085	7.66273	7.64120	7.61606
608		7.66544	7.67680	7.67255	7.64129
626		7.78610	7.74223	7.75006	7.76198
644		7.79704	7.75238	7.82334	7.80810
662		7.83128	7.76720	7.84406	7.80140
680		7.83495	7.77079	7.84005	7.79205
698		7.80558	7.79140	7.83706	7.83448
716		7.85614	7.93054	7.92626	7.91703
734		7.92935	7.95699	7.92269	7.95387
752		7.97744	7.92793	7.92730	7.95413
770		7.96788	7.95324	7.99494	7.98510
788		7.94922	8.00462	8.00019	7.97000
806		8.04092	8.05826	8.04179	8.03275
824		8.08813	8.07300	8.08875	8.11680
842		8.05622	8.08464	8.08338	8.10558
860		8.08247	8.08322	8.08945	8.08671
878		8.06685	8.07609	8.05277	8.06528
896		8.10921	8.10590	8.07360	8.04410
914		8.12787	8.05778	8.10277	8.03815
932		8.05892	7.99768	8.02255	7.99635
950		8.02662	7.96211	7.99332	7.96916
968		7.96131	7.89960	7.95912	7.96982
986		7.98931	7.94253	7.99971	8.00598
1004		8.04274	8.03480	8.14460	8.10403
1022		8.16194	8.14151	8.29005	8.25086
1040		8.37805	8.32607	8.48794	8.45616
1058		8.62890	8.62634	8.72552	8.68731
1076		8.89359	8.88079	8.92331	8.87758
1094		9.13335	9.05494	9.04766	8.95398
1112		9.26923	9.16097	9.12374	9.04773
1130		9.26800	9.23081	9.17013	9.05959
1148		9.32132	9.32455	9.17401	9.06821
1166		9.47562	9.42839	9.28167	9.19418
1184		9.58695	9.49854	9.31228	9.22201

## Appendix 5—Tabulated Instantaneous CTE Results (cont.)

Temperature, F	Instantaneous CTE- $\mu\text{in/inF}$			
	SpecID	2-L2-1	2-L2-2	T7-1-1
Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus
1202	9.55570	9.45880	9.22277	9.17044
1220	9.57168	9.37706	9.16853	9.12909
1238	9.53957	9.32468	9.07874	9.11609
1256	9.44352	9.31443	9.03066	9.08024
1274	9.45663	9.20248	8.93042	9.07259
1292	9.43171	9.18381	8.84093	9.15518
1310	9.38744	9.21860	9.02055	9.25260
1328	9.45401	9.25158	9.28952	9.43758
1346	9.62612	9.47403	9.60874	9.80657
1364	9.85049	9.66987	10.03726	10.29517
1382	10.01446	9.88603	10.44034	10.70326
1400	10.26961	10.19375	10.83220	11.29215
1418	10.62239	10.55181	11.27237	11.87895
1436	11.06261	10.99749	11.68117	12.32215
1454	11.51301	11.44760	11.96238	12.88640
1472	11.82610	11.79993	12.29177	13.26183
1490	12.19246	12.16284	12.60267	13.50977
1508	12.38156	12.43819	12.89106	13.78050
1526	12.75945	12.72550	13.13192	14.01451
1544	13.11016	13.04251	13.40296	14.20645
1562	13.26350	13.18762	13.63933	14.24593
1580	13.44390	13.39252	13.75482	14.26831
1598	13.56107	13.52976	13.95597	14.38600
1616	13.75714	13.73964	14.12772	14.55959
1634	13.87710	13.94656	14.35144	14.56149
1652	14.09056	14.07432	14.55704	14.69275
1670	14.26619	14.25999	14.83210	14.93051
1688	14.46715	14.50611	15.09443	15.06271
1706	14.81191	14.86748	15.38813	15.28897
1724	15.19850	15.15608	15.76943	15.50484
1742	15.39910	15.46360	15.88844	15.58414
1760	15.67551	15.77489	15.84535	15.69881
1778	16.00837	16.05228	15.98817	15.71424
1796	16.32033	16.39528	16.09377	15.76221
1814	16.65580	16.67448	16.15512	16.03647
1832	17.12469	16.95861	16.41685	16.27884
1850	17.50464	17.29777	16.68638	16.60441
1868	17.66952	17.60236	17.00183	16.97019
1886	18.21630	18.07047	17.38981	17.31644
1904	18.81093	18.36966	17.62387	17.75802
1922	19.12722	18.63620	17.76382	18.11358
1940	19.64027	19.28404	17.85471	18.36380
1958	20.23020	19.73597	18.12981	18.55184
1976	20.68488	20.20276	18.45650	18.95587
1994	21.16618	20.91525	18.04515	18.89172
2012	21.64171	21.51263	16.91584	17.66648
2030	22.44449	22.02825	15.50050	15.02985
2048	21.60569	20.43019	15.20538	14.13186
2066	18.72114	17.61270	14.72262	14.27746
2084	16.15604	15.71210	13.08115	12.91224
2102	14.07457	13.52167	11.17095	11.01422
2120	10.78872	9.93061	9.36475	9.85164
2138	8.20523	6.86235	9.20720	9.62396
2156	6.84959	4.72670	8.64562	8.19074
2174	5.82714	3.31262	7.58576	7.04136
2192	6.63331	4.39647	8.53914	8.05148

## Appendix 6—Tabulated Mean CTE Results

Temperature- F	Mean CTE- $\mu$ in/inF				
	SpecID	2-L2-1	2-L2-2	T7-1-1	T7-1-2
	Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus
212		6.90090	6.89242	6.85555	6.81599
230		6.90712	6.90317	6.86834	6.84078
248		6.91704	6.90931	6.88162	6.85220
266		6.93033	6.92299	6.90373	6.87002
284		6.94676	6.94192	6.92111	6.88870
302		6.96492	6.96027	6.94160	6.91353
320		6.97884	6.97673	6.95848	6.93459
338		6.99072	6.98705	6.97108	6.94439
356		7.00339	7.00050	6.98487	6.96157
374		7.02334	7.02260	7.00675	6.98657
392		7.03575	7.04060	7.02472	7.00687
410		7.05454	7.05560	7.04144	7.01964
428		7.07077	7.07007	7.05589	7.03491
446		7.08224	7.08425	7.07173	7.04991
464		7.10068	7.10155	7.09043	7.06899
482		7.11621	7.11693	7.10754	7.08698
500		7.13085	7.13381	7.12316	7.10330
518		7.14523	7.14857	7.13786	7.11944
536		7.15903	7.16335	7.15390	7.13589
554		7.17349	7.18204	7.17126	7.15428
572		7.18778	7.19985	7.18927	7.17194
590		7.20074	7.21581	7.20489	7.18828
608		7.21394	7.23093	7.21999	7.20228
626		7.23087	7.24611	7.23556	7.21853
644		7.24854	7.26230	7.25307	7.23647
662		7.26542	7.27685	7.27065	7.25373
680		7.28251	7.29188	7.28759	7.26968
698		7.29766	7.30526	7.30321	7.28499
716		7.31232	7.32072	7.31897	7.30143
734		7.32805	7.33802	7.33603	7.31874
752		7.34457	7.35373	7.35084	7.33545
770		7.36085	7.36875	7.36688	7.35159
788		7.37567	7.38393	7.38253	7.36754
806		7.39046	7.39978	7.39807	7.38241
824		7.40697	7.41573	7.41397	7.39997
842		7.42230	7.43107	7.42979	7.41582
860		7.43693	7.44603	7.44448	7.43141
878		7.45133	7.46001	7.45878	7.44562
896		7.46475	7.47369	7.47137	7.45896
914		7.47913	7.48693	7.48498	7.47120
932		7.49177	7.49795	7.49692	7.48284
950		7.50305	7.50794	7.50731	7.49274
968		7.51295	7.51634	7.51690	7.50247
986		7.52165	7.52400	7.52558	7.51169
1004		7.53143	7.53305	7.53614	7.52225
1022		7.54174	7.54338	7.54895	7.53437
1040		7.55538	7.55607	7.56439	7.54359
1058		7.57237	7.57255	7.58333	7.56805
1076		7.59380	7.59403	7.60562	7.58997
1094		7.61858	7.61799	7.62991	7.61332
1112		7.64627	7.64400	7.65506	7.63710
1130		7.67376	7.67010	7.68038	7.66147
1148		7.70064	7.69702	7.70533	7.68452
1166		7.72834	7.72440	7.72993	7.70824
1184		7.75765	7.75268	7.75574	7.73267

## Appendix 6—Tabulated Mean CTE Results (cont.)

Temperature- F	Mean CTE- $\mu$ in/inF			
	SpecID	2-L2-1	2-L2-2	T7-1-1
Disk	Supersolvus	Supersolvus	Subsolvus	Subsolvus
1202	7.78658	7.78013	7.77953	7.75587
1220	7.81410	7.80578	7.80176	7.77766
1238	7.84125	7.82942	7.82209	7.79827
1256	7.86607	7.85201	7.84067	7.81810
1274	7.88962	7.87324	7.85790	7.83669
1292	7.91265	7.89221	7.87279	7.85544
1310	7.93423	7.91148	7.88771	7.87498
1328	7.95533	7.93011	7.90601	7.89579
1346	7.97754	7.95012	7.92745	7.91987
1364	8.00198	7.97287	7.95380	7.94942
1382	8.02859	7.99735	7.98514	7.98457
1400	8.05680	8.02499	8.02098	8.02468
1418	8.08879	8.05615	8.06127	8.07276
1436	8.12472	8.09188	8.10640	8.12549
1454	8.16605	8.13256	8.15475	8.18364
1472	8.21100	8.17749	8.20549	8.24674
1490	8.25894	8.22546	8.25940	8.31167
1508	8.30978	8.27675	8.31532	8.37841
1526	8.36153	8.32953	8.37356	8.44655
1544	8.41818	8.38537	8.43293	8.51570
1562	8.47517	8.44241	8.49459	8.58472
1580	8.53364	8.49994	8.55642	8.65207
1598	8.59185	8.55861	8.61870	8.71883
1616	8.65086	8.61721	8.68187	8.78563
1634	8.71029	8.67769	8.74555	8.85243
1652	8.77000	8.73804	8.81065	8.91741
1670	8.83105	8.79918	8.87642	8.98407
1688	8.89224	8.86097	8.94440	9.05065
1706	8.95545	8.92503	9.01320	9.11801
1724	9.02108	8.99129	9.08479	9.18623
1742	9.08903	9.05909	9.15754	9.25486
1760	9.15707	9.12901	9.22898	9.32249
1778	9.22788	9.20037	9.29900	9.39016
1796	9.29975	9.27348	9.36965	9.45578
1814	9.37419	9.34850	9.43896	9.52232
1832	9.45034	9.42454	9.50881	9.58998
1850	9.53045	9.50242	9.57995	9.65910
1868	9.61073	9.58189	9.65252	9.73040
1886	9.69290	9.66335	9.72716	9.80381
1904	9.77960	9.74778	9.80372	9.87946
1922	9.86903	9.83233	9.88019	9.95797
1940	9.96001	9.91993	9.95664	10.03747
1958	10.05539	10.01173	10.03269	10.11788
1976	10.15337	10.10520	10.11099	10.19881
1994	10.25415	10.20298	10.18780	10.28156
2012	10.35730	10.30503	10.25566	10.35613
2030	10.46408	10.41020	10.31039	10.41273
2048	10.57200	10.51167	10.35449	10.44653
2066	10.68662	10.58708	10.39795	10.48279
2084	10.71844	10.64119	10.42906	10.51041
2102	10.75733	10.67689	10.44463	10.52419
2120	10.77377	10.68759	10.44240	10.52148
2138	10.76002	10.66550	10.43070	10.51520
2156	10.73301	10.62430	10.41991	10.50251
2174	10.69411	10.56609	10.39876	10.47627
2192	10.63977	10.49746	10.36599	10.43733

## Appendix 7—Tabulated Young’s Modulus Results

Temperature- F	Young’s Modulus-Msi								
	SpecID	T7-2-M1L	T7-2-M1S	T7-2-M2L	T7-2-M2S	T7-2-M3L	T7-2-M3S	T7-2-M4L	T7-2-M4S
81		32.62	33.10	32.61	32.91	32.27	32.80	32.59	32.94
86		32.61	33.10	32.59	32.86	32.26	32.75	32.60	32.94
104		32.52	32.97	32.52	32.75	32.18	32.65	32.52	32.79
122		32.42	32.79	32.41	32.60	32.08	32.49	32.42	32.65
140		32.31	32.67	32.30	32.44	31.97	32.34	32.31	32.50
158		32.18	32.55	32.19	32.29	31.85	32.19	32.18	32.36
176		32.05	32.36	32.05	32.19	31.71	32.04	32.05	32.21
194		31.93	32.24	31.93	32.03	31.59	31.94	31.90	32.07
212		31.81	32.12	31.80	31.93	31.48	31.79	31.80	31.97
230		31.69	32.06	31.69	31.83	31.38	31.69	31.68	31.83
248		31.59	31.94	31.58	31.73	31.25	31.59	31.57	31.73
266		31.48	31.82	31.47	31.63	31.16	31.49	31.46	31.64
284		31.38	31.76	31.38	31.52	31.05	31.39	31.35	31.54
302		31.28	31.64	31.27	31.42	30.95	31.29	31.26	31.45
320		31.19	31.58	31.17	31.32	30.86	31.24	31.17	31.35
338		31.10	31.46	31.09	31.22	30.77	31.14	31.07	31.26
356		30.99	31.34	30.99	31.12	30.67	31.04	30.97	31.17
374		30.91	31.28	30.89	31.07	30.58	30.94	30.87	31.07
392		30.81	31.16	30.81	30.97	30.49	30.84	30.79	30.98
410		30.73	31.10	30.71	30.87	30.40	30.74	30.69	30.88
428		30.64	30.98	30.63	30.77	30.31	30.69	30.61	30.79
446		30.56	30.92	30.54	30.72	30.23	30.59	30.51	30.74
464		30.47	30.86	30.46	30.62	30.14	30.49	30.43	30.65
482		30.38	30.75	30.37	30.52	30.06	30.45	30.34	30.55
500		30.30	30.69	30.28	30.47	29.98	30.35	30.26	30.46
518		30.21	30.57	30.19	30.37	29.88	30.25	30.18	30.37
536		30.13	30.51	30.11	30.27	29.80	30.15	30.08	30.27
554		30.05	30.39	30.03	30.22	29.72	30.10	30.00	30.23
572		29.96	30.33	29.94	30.12	29.64	30.00	29.93	30.14
590		29.88	30.27	29.86	30.02	29.56	29.91	29.84	30.04
608		29.80	30.16	29.78	29.97	29.47	29.86	29.75	29.95
626		29.70	30.10	29.68	29.87	29.39	29.76	29.65	29.86
644		29.62	29.98	29.60	29.78	29.30	29.66	29.57	29.81
662		29.52	29.92	29.51	29.68	29.20	29.57	29.49	29.72
680		29.44	29.81	29.42	29.63	29.12	29.52	29.40	29.63
698		29.37	29.75	29.34	29.53	29.04	29.42	29.31	29.53
716		29.28	29.69	29.26	29.43	28.96	29.33	29.23	29.44
734		29.19	29.57	29.18	29.38	28.88	29.28	29.14	29.40
752		29.11	29.52	29.08	29.28	28.80	29.18	29.06	29.31
770		29.03	29.40	29.01	29.19	28.72	29.08	28.98	29.21
788		28.95	29.34	28.93	29.14	28.63	29.04	28.90	29.12
806		28.86	29.23	28.82	29.04	28.54	28.94	28.80	29.03
824		28.77	29.17	28.74	28.94	28.45	28.85	28.72	28.94
842		28.68	29.06	28.66	28.85	28.36	28.75	28.63	28.89
860		28.59	29.00	28.57	28.80	28.28	28.65	28.55	28.80
878		28.51	28.88	28.49	28.70	28.20	28.61	28.46	28.71
896		28.43	28.83	28.41	28.60	28.11	28.51	28.37	28.62
914		28.33	28.77	28.33	28.51	28.03	28.42	28.28	28.53
932		28.25	28.65	28.24	28.46	27.95	28.32	28.65	28.44
950		28.17	28.60	28.15	28.36	27.87	28.27	28.12	28.35
968		28.09	28.48	28.07	28.27	27.78	28.18	28.26	28.31
986		28.00	28.40	27.99	28.22	27.70	28.08	28.18	28.22
1004		27.92	28.31	27.91	28.12	27.62	27.99		28.13
1022		27.84	28.21	27.82	27.98	27.53	27.90		28.04
1040		27.75	28.11	27.73	27.93	27.44	27.80		27.90
1058		27.64	28.01	27.62	27.79	27.35	27.71	27.82	27.81
1076		27.54	27.91	27.53	27.69	27.24	27.61		27.72

## Appendix 7—Tabulated Young’s Modulus Results (cont.)

Temperature- F	Young's Modulus-Msi								
	SpecID	T7-2-M1L	T7-2-M1S	T7-2-M2L	T7-2-M2S	T7-2-M3L	T7-2-M3S	T7-2-M4L	T7-2-M4S
	1094	27.44	27.80	27.42	27.60	27.15	27.47	27.39	27.59
	1112	27.33	27.70	27.33	27.51	27.03	27.38		27.50
	1130	27.23	27.59	27.21	27.36	26.93	27.29	27.18	27.41
	1148	27.12	27.48	27.11	27.27	26.84	27.20	27.08	27.28
	1166	27.02	27.37	27.01	27.17	26.73	27.06		27.19
	1184	26.92	27.27	26.91	27.08	26.63	26.96	26.87	27.10
	1202	26.81	27.15	26.80	26.99	26.52	26.87	26.76	26.97
	1220	26.68	27.05	26.68	26.85	26.41	26.78	26.85	26.88
	1238	26.58	26.93	26.57	26.75	26.30	26.64	26.54	26.75
	1256	26.47	26.83	26.47	26.61	26.19	26.55	26.44	26.67
	1274	26.37	26.72	26.36	26.52	26.08	26.46	26.32	26.64
	1292	26.26	26.61	26.25	26.43	25.98	26.32	26.21	26.45
	1310	26.15	26.51	26.15	26.29	25.87	26.23	26.11	26.32
	1328	26.05	26.40	26.04	26.20	25.76	26.14	26.00	26.23
	1346	25.94	26.30	25.93	26.10	25.66	26.00	25.90	26.10
	1364	25.83	26.19	25.81	25.97	25.55	25.91	25.79	26.01
	1382	25.72	26.08	25.70	25.87	25.44	25.82	25.69	25.89
	1400	25.61	25.96	25.59	25.78	25.34	25.68	25.58	25.80
	1418	25.48	25.84	25.47	25.64	25.22	25.59	25.46	25.67
	1436	25.36	25.73	25.35	25.51	25.10	25.46	25.34	25.54
	1454	25.24	25.60	25.22	25.42	24.97	25.32	25.21	25.41
	1472	25.11	25.48	25.09	25.28	24.84	25.23	25.09	25.33
	1490	24.98	25.36	24.96	25.14	24.71	25.10	24.96	25.20
	1508	24.84	25.24	24.82	25.05	24.57	24.97	24.81	25.07
	1526	24.70	25.11	24.68	24.92	24.44	24.83	24.68	24.95
	1544	24.57	24.99	24.54	24.78	24.29	24.74	24.72	24.82
	1562	24.43	24.86	24.59	24.65	24.17	24.57	24.58	24.69
	1580		24.72	24.45	24.51	24.22	24.48		24.57
	1598		24.58		24.38		24.30		24.40
	1616		24.44		24.25		24.17		24.28
	1634		24.29		24.11		24.04		24.11
	1652		24.12		23.94		23.87		23.94
	1670		23.95		23.76		23.69		23.78
	1688		23.77		23.58		23.52		23.61
	1706		23.58		23.41		23.35		23.45
	1724		23.40		23.19		23.13		23.25
	1742		23.17		22.97		22.96		23.04
	1760		22.93		22.80		22.71		22.80
	1778		22.69		22.59		22.45		22.60
	1796		22.58		22.29		22.12		22.36
	1814		21.99		21.82		21.78		22.16
	1832				21.44		21.53		21.88
	1850				21.28		21.00		
	1868				21.07		20.71		
	1886				20.78	20.40	20.51		
	1904				20.53	19.83	20.23		
	1922		19.28			19.27	20.03		
	1940		19.11			18.70	19.75		
	1958		18.92			18.37			
	1976		18.63		17.85	17.89			
	1994		18.21		17.75	17.56			
	2012				17.63	17.11			
	2019				17.64	17.07			

## Appendix 8—Tabulated Tensile Results

Disk	SpecID	Av. Cooling Rate Soln to 1600F-F/min	Test Temp-F	0.2% Yield Strength-ksi	Ultimate Tensile Strength-ksi	Elongation-%	Reduction in Area-%
Supersolvus	BT1	75	1100	147.9	220.7	15.0	18
Supersolvus	BT2	70	800	146.7	217.4	20.5	25
Supersolvus	BT3	70	1300	142.3	193.5	21.3	24.5
Supersolvus	BT4	70	75	155.6	227.9	20.7	23
Supersolvus	BST	80	1500	131.8	151.6	3.9	9.5
Supersolvus	BSB	70	400	148.7	220.5	18.7	21.5
Supersolvus	WT1	105	1000	154.3	222.4	13.1	19.5
Supersolvus	WT2	97	75	162.5	232.9	23.9	26
Supersolvus	WT3	95	1200	144.7	213.0	24.7	24
Supersolvus	WT4	95	1000	148.4	215.6	19.6	21.5
Supersolvus	WT5	97	1400	145.2	177.7	11.6	15.5
Supersolvus	WT6	83	1300	146.0	194.9	15.0	18
Supersolvus	WTS	87	1100	145.3	218.5	17.9	22.2
Supersolvus	RT1	165	1100	157.1	226.5	14.0	17.5
Supersolvus	RT2	160	1400	156.9	168.7	5.8	9
Supersolvus	RT3	155	1300	149.3	192.1	9.9	14.5
Supersolvus	RT5	120	1200	150.3	220.3	14.3	18.5
Supersolvus	RT6	115	400	151.6	221.1	15.3	19.8
Supersolvus	RT7	110	800	152.6	217.5	21.3	23
Supersolvus	RT8	115	1400	142.8	168.5	10.7	18
Subsolvus	BT1	360	1100	173.4	251.4	19.7	19.5
Subsolvus	BT2	325	800	173.5	242.9	18.1	21.5
Subsolvus	BT3	325	1300	168.6	192.0	13.6	19.5
Subsolvus	BT4	360	75	186.4	253.1	20.3	26
Subsolvus	BST	450	1300	169.7	211.3	12.0	15.9
Subsolvus	BSB	500	400	179.7	247.9	18.3	19.1
Subsolvus	WT1	570	1000	172.2	241.8	19.7	18.5
Subsolvus	WT2	375	75	187.5	252.3	21.8	26
Subsolvus	WT3	350	1200	171.6	223.7	13.7	17
Subsolvus	WT4	360	1000	172.5	240.9	20.1	26.5
Subsolvus	WT5	490	1400	161.5	177.9	7.1	11
Subsolvus	WT6	360	1300	169.9	199.5	9.2	14
Subsolvus	WTS	375	1200	167.0	223	10.0	15.5
Subsolvus	RT1	725	1100	173.5	243.1	14.0	16.5
Subsolvus	RT2	600	1400	165.9	170.6	5.4	11
Subsolvus	RT3-B	400	1300	171.3	194.3	8.1	9.5
Subsolvus	RT4	590	1500	134.1	154.7	9.3	8.5
Subsolvus	RT6	420	400	174.8	241.9	18.9	25
Subsolvus	RT7	420	800	175.8	242.7	16.9	21
Subsolvus	RT8	510	1400	159.0	176.1	10.0	7.5

## Appendix 9—Tabulated Notch Tensile Results

Disk	SpecID	Av. Cooling Rate Soln to 1600F-F/min	Temp-F	Ultimate Tensile Strength-ksi
Supersolvus	BNT1	78	75	266.6
Supersolvus	BNT3	80	1000	254.4
Supersolvus	BNT4	77	1300	259.4
Supersolvus	BNT5	77	1100	251.4
Supersolvus	WNT1	95	1200	245.8
Supersolvus	WNT2	85	800	256.1
Supersolvus	WNT3	83	1400	241.5
Supersolvus	WNT4	85	1100	250.9
Subsolvus	BNT1	600	75	297.5
Subsolvus	BNT2	375	400	280.3
Subsolvus	BNT3	320	1000	284.6
Subsolvus	BNT4	320	1300	252.6
Subsolvus	BNT5	420	1100	274.5
Subsolvus	WNT1	430	1200	268.6
Subsolvus	WNT2	325	800	284.5
Subsolvus	WNT3	325	1400	225.1
Subsolvus	WNT4	480	1100	284.4

## Appendix 10—Tabulated creep results

Disk	SpecID	Average Cooling Rate Soln to 1600F-F/min	Temp-F	Creep Stress-ksi	0.2% Creep Time-h	Rupture Life-h	Rupture Elongation-%	Rupture Reduction in Area-%
Supersolvus	BC1	75	1300	100	557	1691.9	7.3	9.8
Supersolvus	BC2	65	1200	135	233			
Supersolvus	WC1	115	1400	80	153			
Supersolvus	WC2	100	1300	95	710			
Supersolvus	WC3	100	1500	35	1590	2231.4	2.9	4.2
Supersolvus	WC4	110	1400	100	14.8			
Supersolvus	WC5	100	1500	50	132			
Supersolvus	WC6	100	1400	65	680			
Supersolvus	WC7	110	1500	35	935			
Supersolvus	WC8	100	1400	80	86			
Supersolvus	WC9	125	1300	125	46.6			
Supersolvus	WC10	110	1500	65	42.4	141.4	14.2	16.2
Supersolvus	WC11	110	1200	125	1347	3574.2	3.2	7.3
Supersolvus	RC1	135	1300	100	895	1881.7	5.4	8.5
Supersolvus	RC2	130	1500	50	93.6			
Supersolvus	RC3	125	1400	65	970	1849.7	4.0	5.7
Supersolvus	RC4	110	1300	110	183			
Subsolvus	BC1	685	1300	100	495.2	886.7	7.1	10.1
Subsolvus	BC2	685	1200	135	1260			
Subsolvus	WC1	650	1300	80	1380	2647.1	8.4	13.3
Subsolvus	WC2	400	1400	35	420			
Subsolvus	WC3	500	1500	35	17.7	157.1		
Subsolvus	WC4	650	1400	65	50			
Subsolvus	WC5	400	1300	80	415			
Subsolvus	WC6	520	1200	125	1616	5265	6.7	11.9
Subsolvus	WC7	725	1400	35	225			
Subsolvus	WC8	560	1200	150	202			
Subsolvus	WC9	670	1300	125	139	224	5.7	9.6
Subsolvus	WC10	425	1200	150	94.5			
Subsolvus	WC11	525	1400	100	5.7	34	5.9	11.2
Subsolvus	RC1	700	1300	100	86	671.5	9.6	14.2
Subsolvus	RC2	550	1500	50	4.3			
Subsolvus	RC3	675	1200	135	770			
Subsolvus	RC4	575	1400	65	33			

## Appendix 11—Tabulated Low Cycle Fatigue Results

Disk	SpecID	Av. Cooling Rate Soln to 1600F- F/min	Temperature- F	Strain Range-%	Fatigue life-cycles
Supersolvus	BL1	87	800	1.196	3,033
Supersolvus	BL2	80	1300	0.8	6,937
Supersolvus	BL3	78	800	0.598	48,725
Supersolvus	BL4	75	800	0.598	81,939
Supersolvus	BL5	75	800	0.598	94,733
Supersolvus	BL13	75	800	0.997	8,125
Supersolvus	WL2	110	800	0.798	20,254
Supersolvus	RL2	110	800	1.192	3,150
Supersolvus	RL3	132	800	0.799	28,195
Supersolvus	RL5	130	800	0.998	6,986
Supersolvus	RL8	130	800	0.597	77,950
Supersolvus	BL6	83	1300	0.597	332,061
Supersolvus	BL7	78	1300	0.598	223,970
Supersolvus	BL8	75	1300	0.598	10,366
Supersolvus	BL9	95	1300	1.195	1,023
Supersolvus	BL11	85	1300	0.999	2,557
Supersolvus	BL12	85	1300	0.797	7,128
Supersolvus	WL3	90	1300	0.999	2,157
Supersolvus	RL1	117	1300	0.798	7,128
Supersolvus	RL4	125	1300	1.199	1,038
Supersolvus	RL7	135	1300	0.599	246,425
Subsolvus	BL1	400	800	1.199	6,586
Subsolvus	BL3	350	800	0.598	350,207
Subsolvus	BL4	275	800	0.6	572,745
Subsolvus	BL5	375	800	0.597	338,501
Subsolvus	BL13	300	800	0.998	8,134
Subsolvus	WL2	425	800	0.798	104,771
Subsolvus	RL2	440	800	1.196	8,225
Subsolvus	RL3	550	800	0.8	68,356
Subsolvus	RL5	550	800	0.999	7,547
Subsolvus	RL8	520	800	0.596	307,903
Subsolvus	BL2	300	1300	0.798	44,737
Subsolvus	BL6	325	1300	0.6	9,529,316
Subsolvus	BL7	275	1300	0.594	916,939
Subsolvus	BL8	350	1300	0.597	2,557,193
Subsolvus	BL9	425	1300	1.197	499
Subsolvus	BL11	320	1300	0.997	16,951
Subsolvus	BL12	300	1300	0.797	12,185
Subsolvus	WL1	525	1300	0.999	3,121
Subsolvus	RL1	525	1300	0.802	9,133
Subsolvus	RL4	490	1300	1.195	1,214
Subsolvus	RL7	560	1300	0.601	963,423

## Appendix 12—Tabulated Notch Fatigue Results

Disk	SpecID	Av. Cooling Rate Soln to 1600F-F/min	Temperature-F	Maximum Stress-ksi	LCF or FCG life -cycles	Notes
Supersolvus	BNL2	97	800	158	8,122	5Hz
Supersolvus	RNL3	130	800	137	15,061	5Hz
Supersolvus	BNL6	75	800	115	29,744	5Hz
Supersolvus	BNL5	75	800	94.5	218,404	5Hz
Supersolvus	RNL4	120	1300	137	4,675	5Hz
Supersolvus	BNL4	85	1300	126.5	18,242	5Hz
Supersolvus	RNL1	105	1300	116	187,412	5Hz
Supersolvus	BNL1	115	1300	126.5	456	90s dwell
Supersolvus	RNL2	100	1300	137	1,163	90s dwell
Subsolvus	BNL6	360	800	158	9,642	5Hz
Subsolvus	RNL3	550	800	137	15,831	5Hz
Subsolvus	BNL5	300	800	115	51,207	5Hz
Subsolvus	BNL4	350	800	105	621,145	5Hz
Subsolvus	RNL2	420	800	94.5	2560007+	5Hz, Runout
Subsolvus	BNL2	400	1300	158	2,168	5Hz
Subsolvus	RNL4	450	1300	137	57,722	5Hz
Subsolvus	BNL1	730	1300	115	2,163,114	5Hz
Subsolvus	RNL6	450	1300	126.5	14,112	90s dwell
Subsolvus	RNL1	500	1300	126.5	57	90s dwell

## Appendix 13—Tabulated Fatigue Crack Growth Results

Disk	SpecID	Average Cooling Rate Soln to 1600F-F/min	Temperature-F	da/dt at 20 ksi*in.5, in./sec	da/dt at 25 ksi*in.5, in./sec	da/dn at 20 ksi*in.5, in/cyc	da/dn at 25 ksi*in.5, in/cyc	Test Type
Supersolvus	BK2	66	800			2.7E-06	6.0E-06	0.33Hz
Supersolvus	WK1	110	75			5.0E-07	2.2E-06	0.33Hz
Supersolvus	WK2	90	400			9.5E-07	3.2E-06	0.33Hz
Supersolvus	RK3	110	1200			5.8E-06	9.8E-06	0.33Hz
Supersolvus	RK4	110	1300			7.3E-06	1.8E-05	0.33Hz
Supersolvus	BK1	66	1200	1.0E-07	3.9E-07			90s dwell
Supersolvus	RK1	130	1300	2.0E-06	4.5E-06			90s dwell
Supersolvus	RK2	130	1200	2.0E-07	3.2E-07			90s dwell
Subsolvus	BK2	360	800			4.0E-06	9.0E-06	0.33Hz
Subsolvus	WK1	425	75			2.0E-06	4.7E-06	0.33Hz
Subsolvus	WK2	340	400			2.2E-06	5.0E-06	0.33Hz
Subsolvus	RK3	425	1200			1.8E-05	3.5E-05	0.33Hz
Subsolvus	RK4	425	1300			2.8E-05	5.5E-05	0.33Hz
Subsolvus	BK1	360	1200	8.0E-07	1.8E-06			90s dwell
Subsolvus	RK1	470	1300		2.5E-05			90s dwell
Subsolvus	RK2	470	1200	8.5E-07	1.8E-06			90s dwell

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